2009 NEHRP Recommended Seismic Provisions:

Training and Instructional Materials

FEMA P-752 CD / June 2013

FEMA nehrp

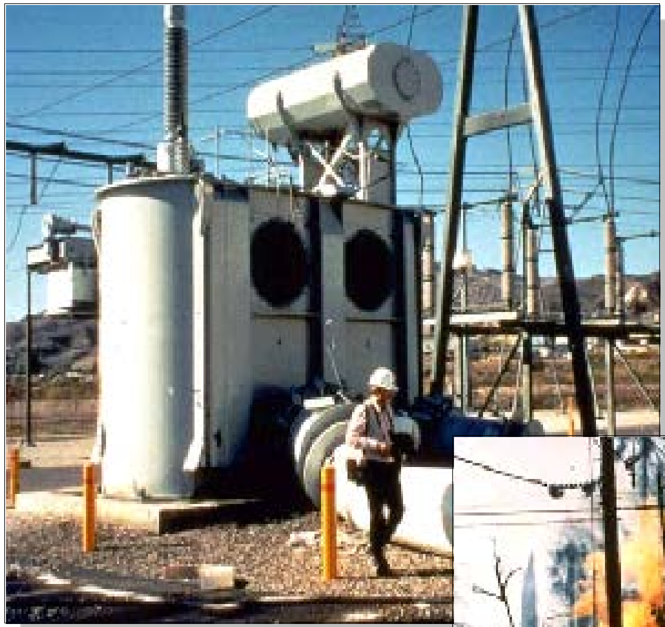
13

Nonbuilding Structure Design

By J. G. (Greg) Soules, P.E., S.E.

Originally developed by Harold O. Sprague, Jr., P.E.

Nonbuilding Structures



Nonbuilding Structures

Same:

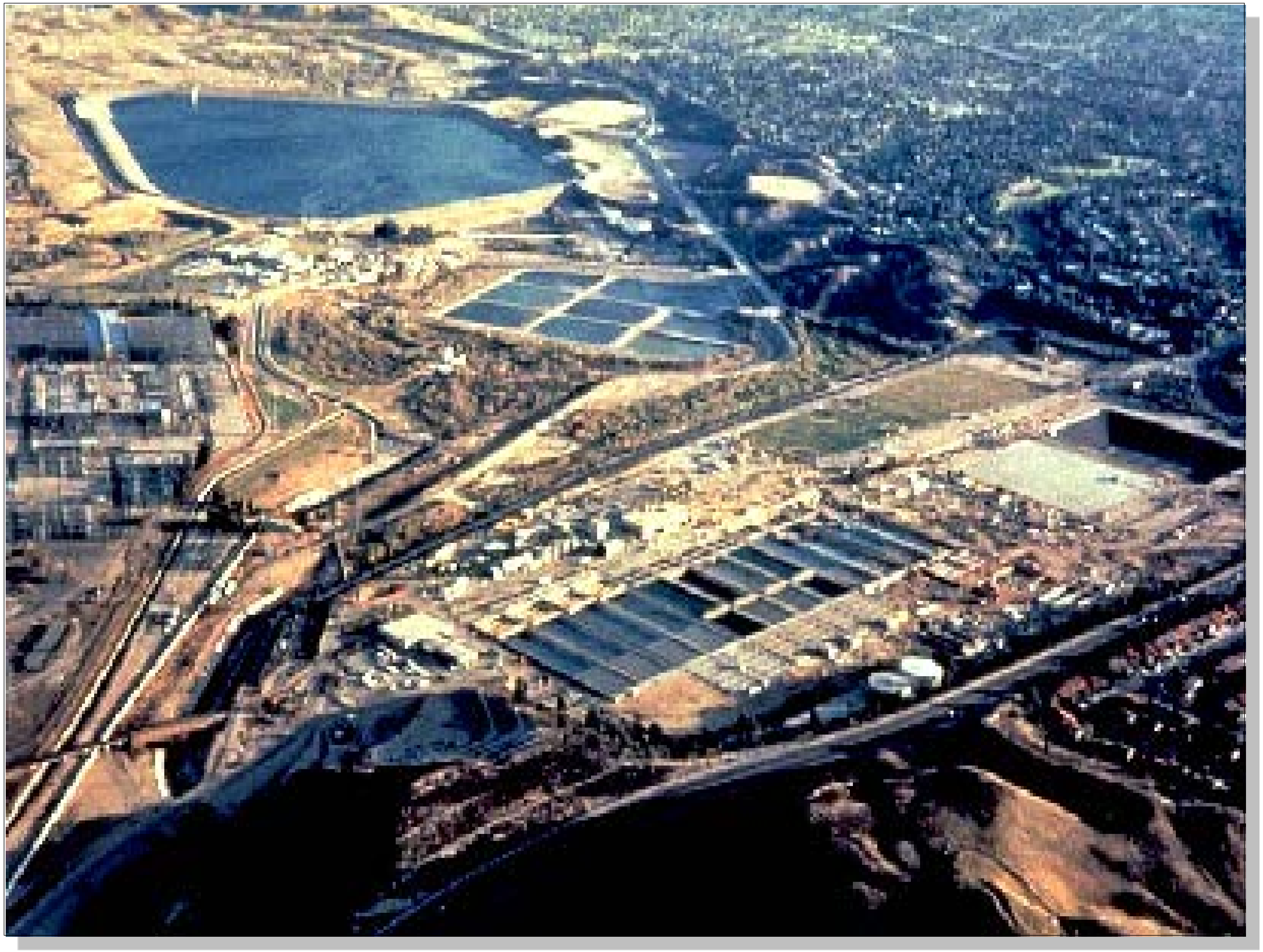
- Basic ground motion hazards
- Basic structural dynamics

Different:

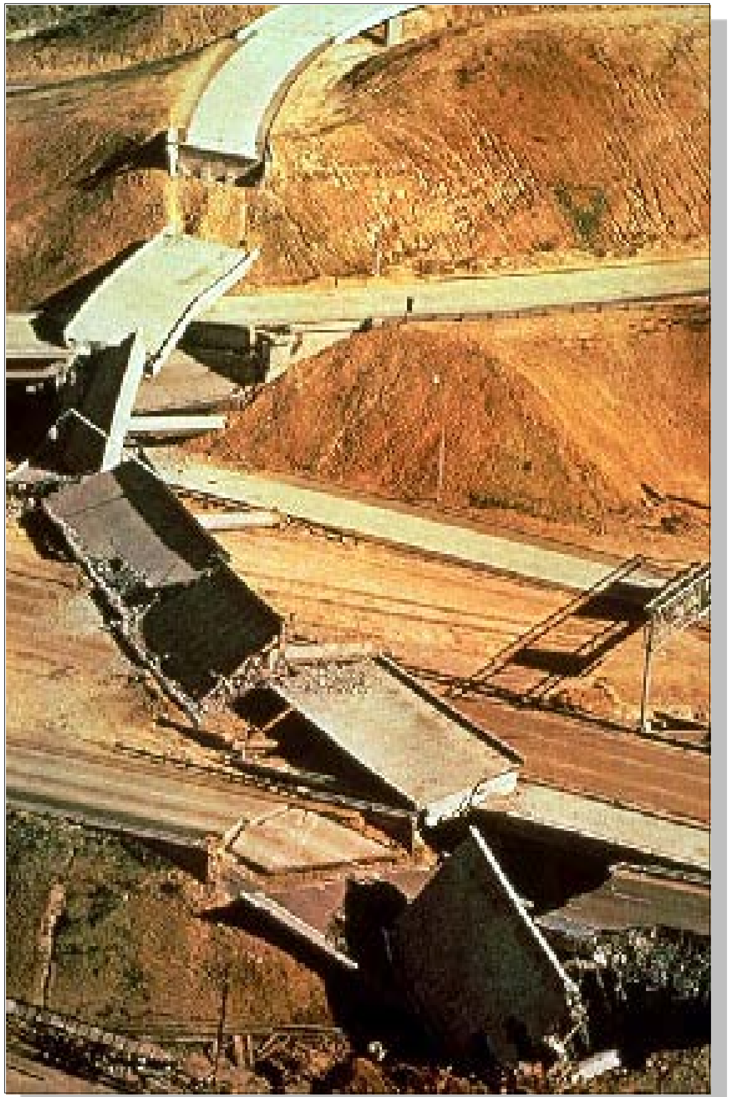
- Structural characteristics
- Fault rupture
- Fluid dynamics
- Performance objectives
- Networked systems

Dams with Damage

Dam and Water Treatment Plant



Bridges



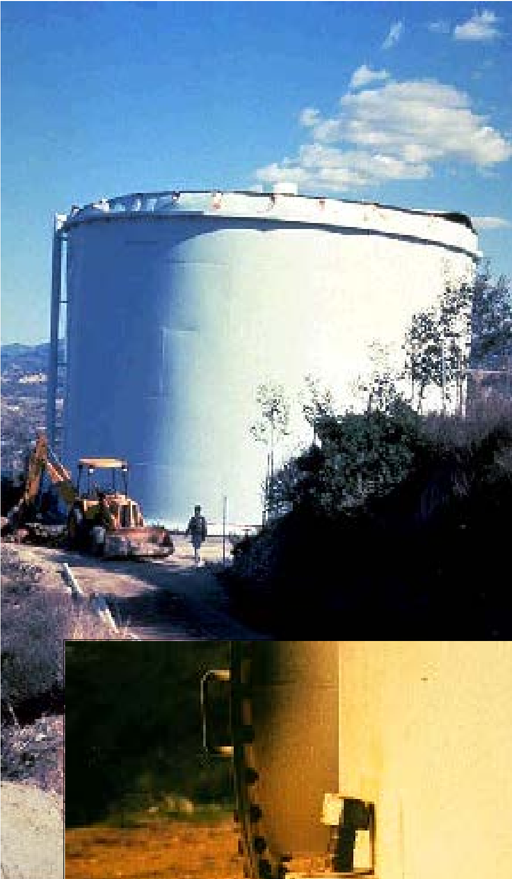
Joints at Long Spans

Elevated Roadways (1)

Elevated Roadways (2)

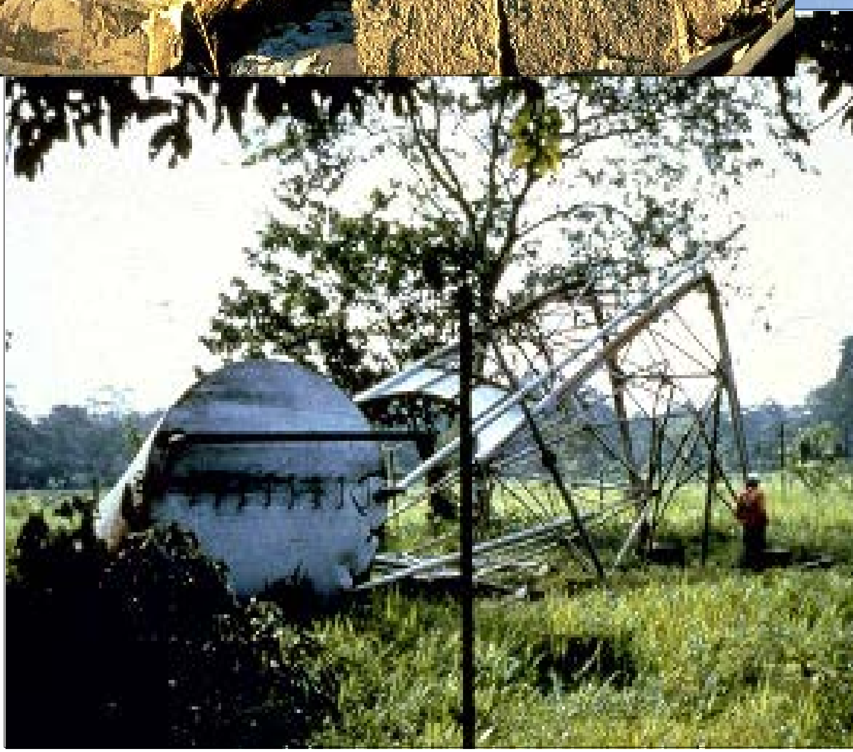
Lack of Redundancy

Tanks

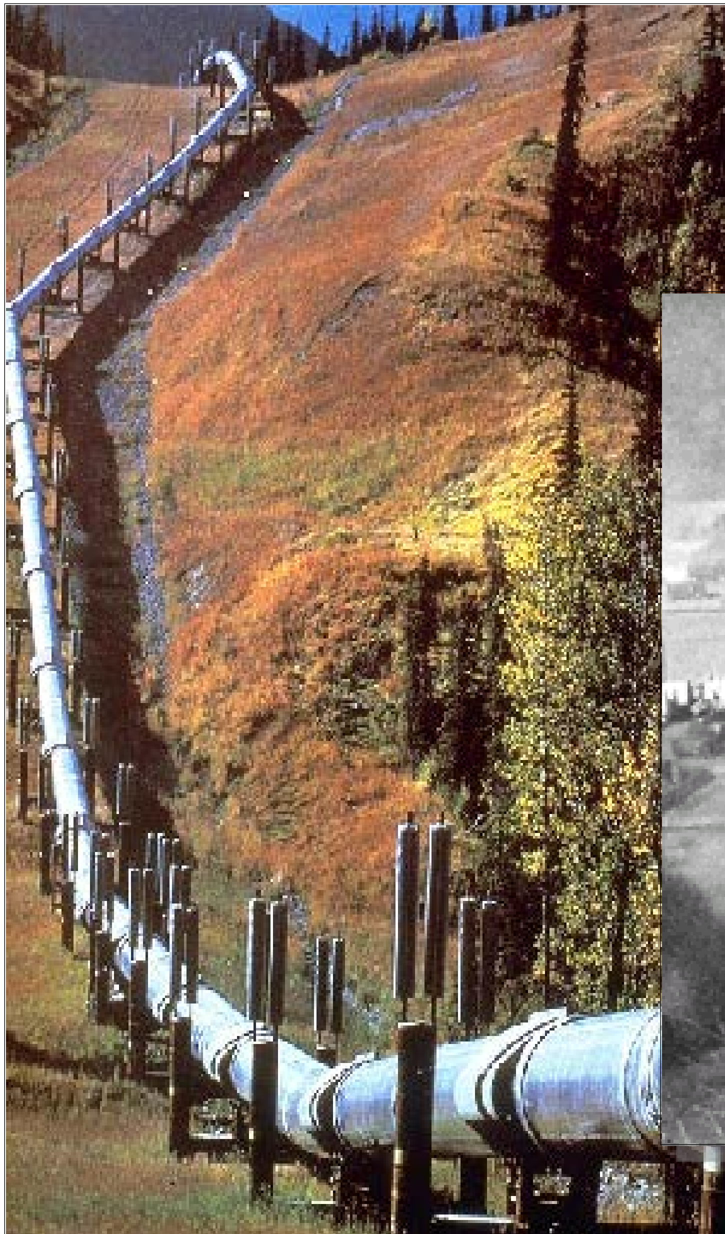


Elephant's foot buckling

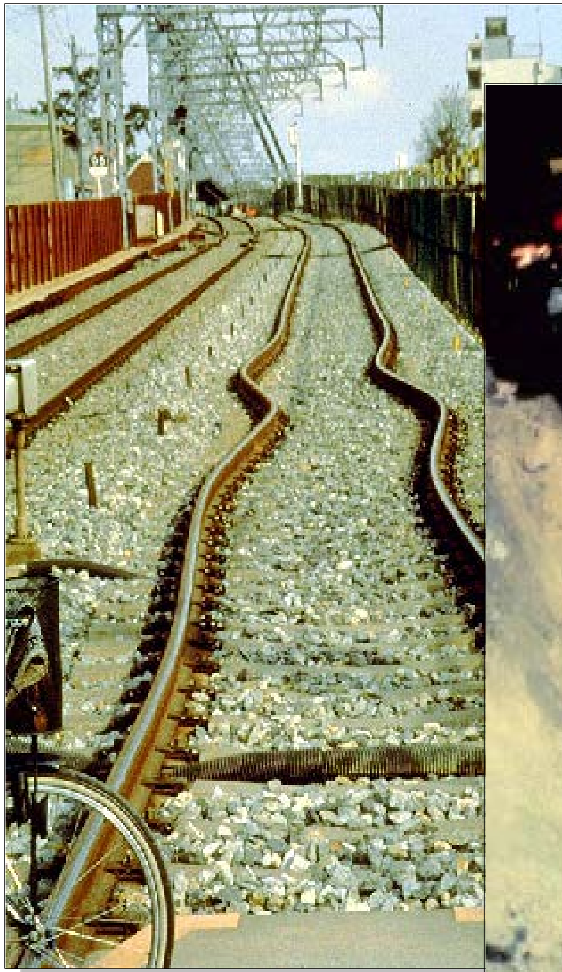
Tanks & Towers

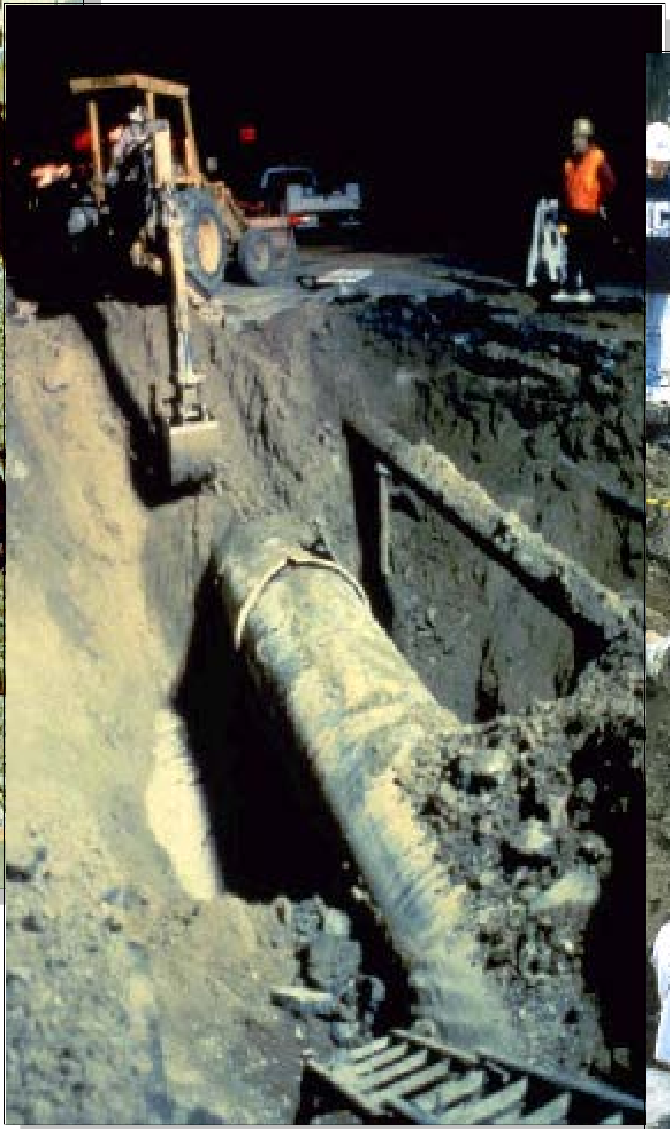


Pipelines

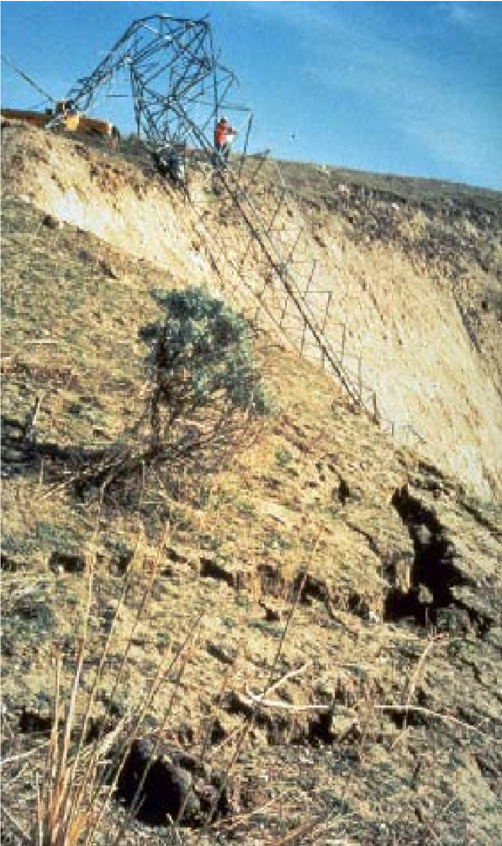


On-Grade and Buried





Electrical Towers and Substations



Nonbuilding Structures in NEHRP *Recommended Provisions*

SCOPE of Chapter 15:

- Self supporting structures that carry gravity loads.
- Nonbuilding structures may be supported by earth or by other structures.

EXCLUSIONS:

- Vehicular and railroad bridges
- Nuclear power plants
- Offshore platforms
- Dams

Nonbuilding Structures

TWO CLASSIFICATIONS included in *Provisions*

1. Nonbuilding structures similar to buildings

- Dynamic response similar to buildings
- Structural systems are designed and constructed similar to buildings
- Use provisions of Chapter 15 and applicable parts of Chapters 11, 12, 14, ...

2. Nonbuilding structures not similar to buildings

- Design and construction results in dynamic response different from buildings
- Use Chapter 15 and "reference documents" for design

Nonbuilding Structures
defined similar to buildings

Examples:

- Pipe racks
- Steel storage racks
- Electric power generation facilities
- Structural towers for tanks & vessels

Nonbuilding Structures
design requirements

Example of Structural Tower that is not Integral with the Supported Tank

Example of Structural Tower that is Integral with the Supported Tank

Nonbuilding Structures
not similar to buildings

- Use “reference documents” for design. Loads and load distributions shall not be less than those given by ASCE 7 / NEHRP *Recommended Provisions*.

Examples:

- Earth retaining structures
- Tanks and vessels
- Telecommunication towers
- Stacks and chimneys

Nonbuilding Structures
not similar to buildings

Examples of approved design standards:

- Liquid Storage Tanks:
  - API 620, *Design and Construction of Large, Welded, Low Pressure Storage Tanks*, 11th edition, 2009
  - API 650, *Welded Steel Tanks for Oil Storage*, 11th Edition, Addendum 1, 2008
  - AWWA D100*, Welded Steel Tanks for Water Storage, 2005*
- Pressure Vessels:
  - ASME BPVC-01, *Boiler and Pressure Vessel Code*, 2004 excluding Section III, Nuclear Components, and Section XI, In-Service Inspection of Nuclear Components

Nonbuilding Structures
design requirements

- **LOADS**
  - Weight, W, for calculating seismic forces includes all dead loads and all normal operating contents
  - (grain, water, etc. for bins and tanks)
- **DRIFT LIMITATIONS**
  - Drift limits of Section 12.12 do not apply - but must maintain stability. P- D check required.
- **FUNDAMENTAL PERIOD**
  - Calculate using substantiated analysis (15.4.4). Do not use approximate period equations 12.8-7, 12.8-8, 12.8-9, and 12.8-10 to determine period of nonbuilding structures.

Nonbuilding Structures
design requirements

- **VERTICAL DISTRIBUTION OF SEISMIC FORCES**
  - Use methods for buildings:
  - ELF or Modal Response Spectrum Analysis
- **NONBUILDING STRUCTURES SUPPORTED BY OTHER STRUCTURES**
  - If W_{nb} < 25% of W_{tot} treat nonbuilding structure as a nonstructural component and design per Chapter 13
  - If W_{nb} ≥ 25% of W_{tot} AND nonbuilding structure is flexible determine seismic forces considering effects of combined structural systems
  - If W_{nb} ≥ 25% of W_{tot} AND nonbuilding structure is rigid treat nonbuilding structure as a nonstructural component and design per Chapter 13 with $R_p = R$

Nonbuilding Structures
design requirements

- Nonbuilding structures supported by other structures see amplified seismic forces in a similar manner as nonstructural components.
- Section 15.3 of ASCE 7 / NEHRP *Recommended Provisions* provides extensive guidance on the design of nonbuilding structures supported by other structures.
- There are 3 possible outcomes when the provisions of Section 15.3 are used as mentioned in the previous slide.

Nonbuilding Structures
design requirements

- Unfortunately, Table 15.4-2 (nonbuilding structures not similar to buildings) contains an error, which conflicts with the provisions of Section 15.3.
- The 3rd entry in Table 15.4-2 is: “Tanks or vessels supported on structural towers similar to buildings”.
- The entry goes on to say: “Use values for the appropriate structure type in the categories for building frame systems and moment resisting frame systems listed in Table 12.2-1 or Table 15.4-1.”
- This entry was not coordinated with Section 15.3 and assumes that the supported tank or vessel is rigid.

Nonbuilding Structures
design requirements

- Most tanks and vessels supported on structural towers will be flexible, especially if fluid-structure interaction is accounted for and/or the flexibility of the support beams is taken into account.
- This entry in Table 15.4-2 has been proposed to be deleted in ASCE 7-10 Supplement 2 and in the 2014 NEHRP *Recommended Provisions*.
- I recommend that you mark through this table entry now!

Nonbuilding Structures
similar to buildings
design requirements

- **SEISMIC COEFFICIENTS AND HEIGHT LIMITS**
  - Use *R* factor from Table 12.2-1 or Table 15-4.1.
  - Table 15-4.1 provides an option where both lower R-values and less restrictive height limitations are specified.
  - This option trades ductility for strength.
  - The R-value / height limit trade-off of Table 15.4-1 only applies to nonbuilding structures similar to buildings and cannot be applied to building structures.

Nonbuilding Structures
similar to buildings
design requirements

Table 15-4-1—SEISMIC COEFFICIENTS FOR NONBUILDING STRUCTURES SIMILAR TO BUILDINGS

Nonbuilding Structure Type	Detailing Requirements	R	Ω_0	C_d	Structural System and Height Limits (ft.)[a, e]				
					A & B	C	D	E	F
Steel storage racks	15.5.3	4	2	3.5	NL	NL	NL	NL	NL
Building frame systems:									
Special steel concentrically braced frames	AISC 341	6	2	5	NL	NL	160	160	100
Ordinary steel concentrically braced frame	AISC 341	3 ¼	2	3 ¼	NL	NL	35[b]	35[b]	NP[b]
With permitted height increase	AISC 341	2 ½	2	2 ½	NL	NL	160	160	100
With unlimited height	AISC 360	1.5	1	1.5	NL	NL	NL	NL	NL

Nonbuilding Structures
design requirements

- **IMPORTANCE FACTOR**
  - Based on Occupancy Category from Table 1-1.
  - Use largest value from applicable reference document (Chapter 23), Table 11.5-1 or as specified elsewhere in Chapter 15.

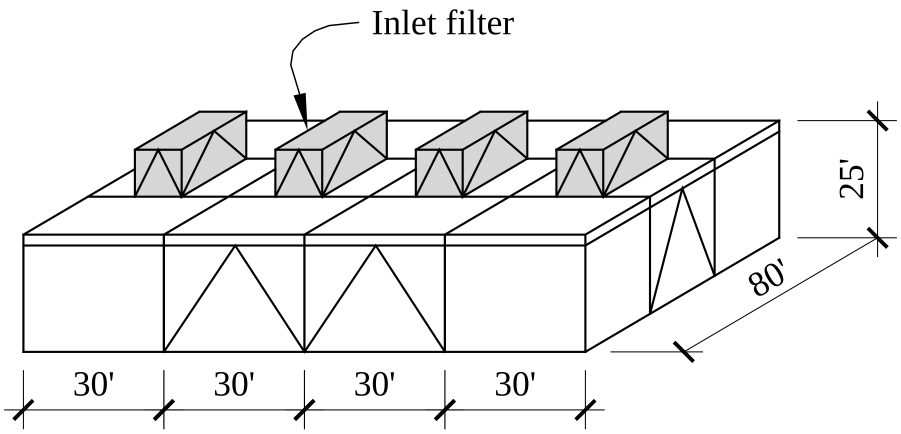
Nonbuilding Structures
design requirements

- **Table 11.5.1: Importance Factor (I)**

Occupancy Category	I
I or II	1.0
III	1.25
IV	1.5

Nonbuilding Structures
design examples

- **Example 13.1 - NONBUILDING STRUCTURES VERSUS NONSTRUCTURAL COMPONENTS**



- Example 13.1.1
  - Combustion turbine building.
  - Building supports four filter units connected in a fashion that couples their dynamic response.
- Example 13.1.2
  - Combustion turbine building.
  - Building supports four filter units that are independent structures.

Nonbuilding Structures
design examples

- Example 13.1.1
  - Four inlet filters = W_{IF} = 4 x 34 kips = 136 kips
  - Support structure = W_{SS} = 288 kips
  - $W_{Combined}$ = 136 kips + 288 kips = 424 kips

$$\frac{W_{IF}}{W_{Combined}} = \frac{136}{424} = 0.321 > 25\%$$

  - Therefore, *Standard* Sec. 15.3.2 is applicable and the requirements of Chapter 15 are to be followed

Nonbuilding Structures
design examples

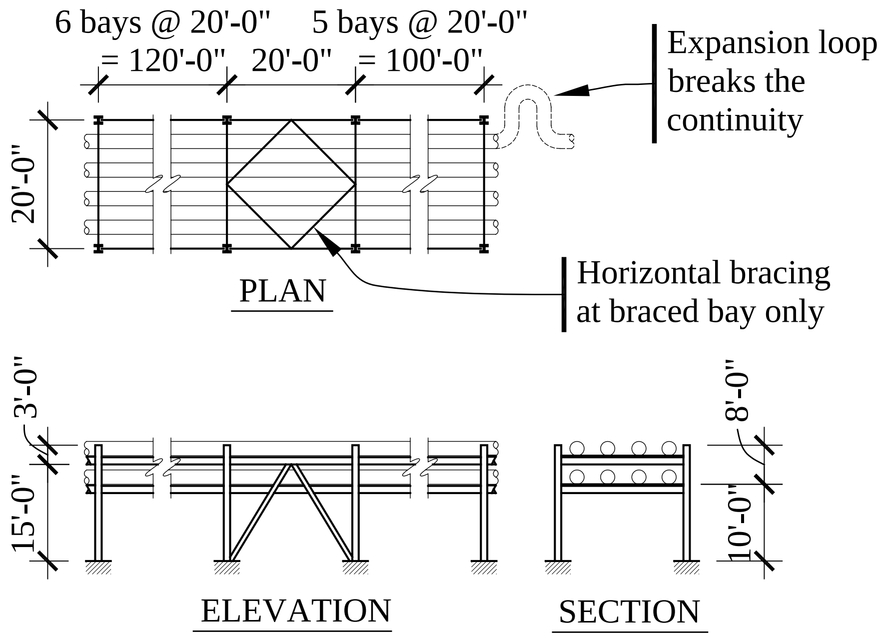
- Example 13.1.2
  - One (effective) inlet filters = W_{IF} = 34 kips
  - Support structure = W_{SS} = 288 kips
  - $W_{Combined}$ = (4 x 34 kips) + 288 kips = 424 kips

$$\frac{W_{IF}}{W_{Combined}} = \frac{34}{424} = 0.08 < 25\%$$

  - Therefore, *Standard* Sec. 15.3.1 is applicable and the requirements of Chapter 13 are to be followed.

Nonbuilding Structures
design examples

- Example 13.2 - PIPE RACK, OXFORD, MISSISSIPPI



- This example illustrates the calculation of design base shears and maximum inelastic displacements for a pipe rack using the equivalent lateral force (ELF) procedure.

Nonbuilding Structures
design examples

- Example 13.2 - PIPE RACK, OXFORD, MISSISSIPPI

- Importance Factor
  - The upper piping carries a toxic material (naphtha) (Occupancy Category III – *Standard* Table 1-1) and the lower piping is required for fire suppression (Occupancy Category IV – *Standard* Table 1-1). The naphtha piping and the fire water piping are included in *Standard* Sec. 1.5.1; therefore, the pipe rack is assigned to Occupancy Category IV based on the more severe category.
  - From *Standard* Table 11.5-1, I = 1.5

Nonbuilding Structures design examples

- Example 13.2 - PIPE RACK, OXFORD, MISSISSIPPI

- *R* Factor Options (Transverse Direction)
  - In *Standard* Table 12.2-1, ordinary steel moment frames are not permitted in Seismic Design Category D. There are several options for ordinary steel moment frames found in *Standard* Table 15.4-1 as follows:
  - *Standard* Table 15.4-1, Ordinary moment frames of steel, *R* = 3.5. According to note c in *Standard* Table 15.4-1, this system is allowed for pipe racks up to 35’ without limitations on the connection type. Option requires the use of the AISC Seismic Provisions.
  - *Standard* Table 15.4-1, Ordinary moment frames of steel with permitted height increase, *R* = 2.5. This option is intended for pipe racks greater than 65’ high and limited to 100’. Option is not applicable for this example.
  - *Standard* Table 15.4-1, Ordinary moment frames of steel with unlimited height, *R*=1. Option does not require the use of the AISC Seismic Provisions.
  - For this example, Option with *R* = 3.5 is chosen.

Nonbuilding Structures
design examples

- Example 13.2 - PIPE RACK, OXFORD, MISSISSIPPI

- Redundancy Factor (Transverse Direction)
  - The seismic force-resisting system is an ordinary moment resisting frame with only two columns in a single frame. The frames repeat in an identical pattern.
  - Loss of moment resistance at the beam-to-column connections at both ends results in a loss of more than 33% in story strength. Therefore, *Standard* Sec. 12.3.4.2 Condition a is not met. The moment frame as described above consists only of a single bay. Therefore, *Standard* Sec. 12.3.4.2 Condition b is not met.
  - The value of ρ in the transverse direction is therefore 1.3.

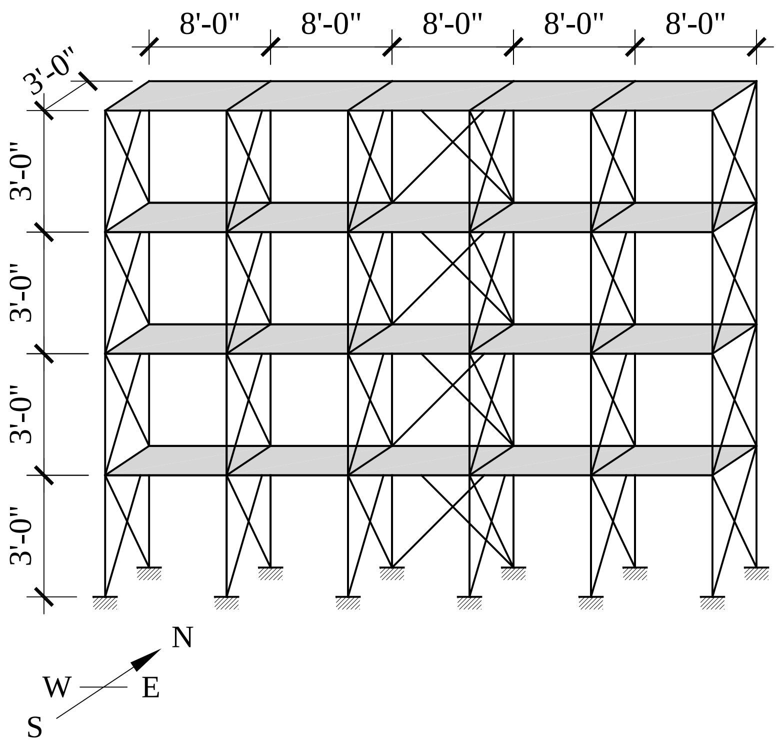
Nonbuilding Structures
design examples

- Example 13.2 - PIPE RACK, OXFORD, MISSISSIPPI

- Orthogonal Loading Requirements
  - For SDC D, *Standard* Sec. 12.5.4 requires that the braced sections of the pipe rack be evaluated using the orthogonal combination rule of *Standard* Sec. 12.5.3a.
  - Two cases must be checked
    - 100% transverse seismic force plus 30% longitudinal seismic force
    - 100% longitudinal seismic force plus 30% transverse seismic force.

Nonbuilding Structures
design examples

- Example 13.3 - STEEL STORAGE RACK, OXFORD, MISSISSIPPI



- This example uses the equivalent lateral force (ELF) procedure to calculate the seismic base shear in the east-west direction for a steel storage rack.

Nonbuilding Structures
design examples

- Example 13.3 - STEEL STORAGE RACK, OXFORD, MISSISSIPPI

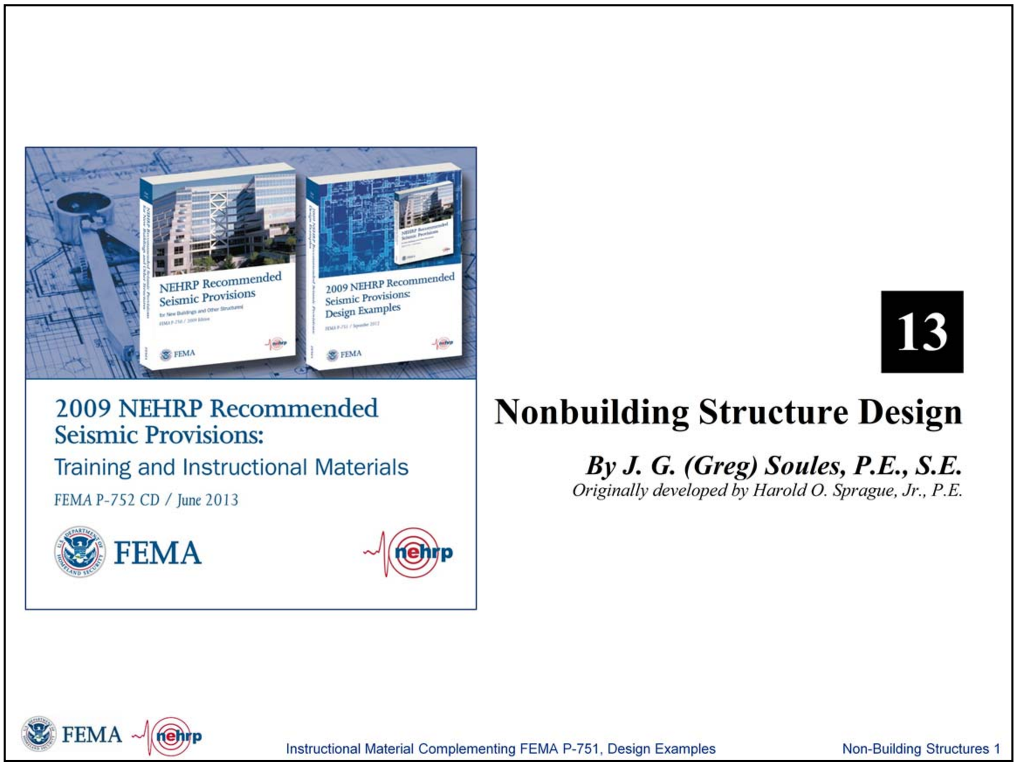
- Importance Factor
  – Use *Standard* Sec. 1.5.1. The storage rack is in a retail facility. Therefore the storage rack is assigned to Occupancy Category II. According to *Standard* Sec. 15.5.3(2) , $I = I_p = 1.5$ because the rack is in an area open to the general public.
- RMI Section 2.6.2 Loading Conditions
  – Load Case 1 – Each rack loaded.
  – Load Case 2 – Only top rack loaded.

Nonbuilding Structures
design examples

- Example 13.3 - STEEL STORAGE RACK, OXFORD, MISSISSIPPI

- Controlling Conditions
  - Condition “1” controls shear demands at all but the top level.
  - Although the overturning moment is larger under condition “1” , the resisting moment is larger than the overturning moment. Under condition “2” the resistance to overturning is less than the applied overturning moment. Therefore, the rack anchors must be designed to resist the uplift induced by the base shear for condition “2”.

Questions?



This unit is only a brief introduction to the subject of earthquake resistant design of nonbuilding structures. It was originally developed by Jim Harris from two primary sources: the content of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* and two slide collections of the Earthquake Engineering Research Institute: the "Annotated Slide Collection" and the "EERI Northridge Earthquake of January 1994 Collection." This unit has been updated by J. G. (Greg) Soules P.E., S.E.

The images here are all taken from the 1994 Northridge event: failed transformers in an electric power distribution substation (Sylmar), fire and flood from breaks in buried gas and water mains (Balboa Blvd, Granada Hills), and demolition of damaged highway interchange structures (Gavin Canyon undercrossing, Interstate 5).

Nonbuilding Structures

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Non-Building Structures 2

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Nonbuilding Structures

Same:

- Basic ground motion hazards
- Basic structural dynamics

Different:

- Structural characteristics
- Fault rupture
- Fluid dynamics
- Performance objectives
- Networked systems

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Non-Building Structures 3

There are many issues with nonbuilding structures that are not considered in earthquake engineering for buildings.

Dams with Damage

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Non-Building Structures 4

Left: San Fernando EQ (1971); partial failure of upstream face of lower Van Norman dam, a 40m high earthfill dam about 20 km from epicenter; pga estimated to be 0.3 to 0.5 g; 80,000 people downstream evacuated for several days until water level could be lowered.

Right; Northridge EQ; Pacoima dam, a concrete arch in a rock canyon; used for flood control, thus low water level; measured 2g pga at abutments; extensive rock slides; opened a 2 inch gap at southern thrust block and created several cracks.

Issues: liquefaction of hydraulic fills; site conditions; hydrodynamic loads; sloshing

Dam and Water Treatment Plant

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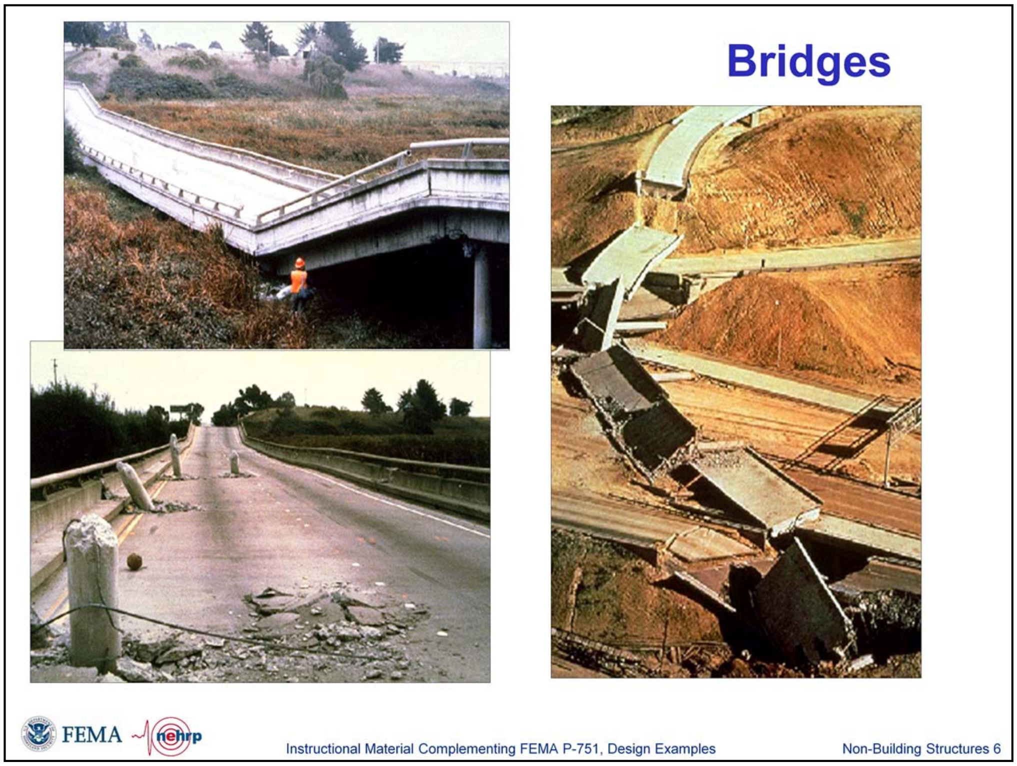
Northridge EQ: Jensen water filtration plant, site of old San Fernando (Van Norman dam) embankment, and new Los Angeles dam above. PGA approached 1g at Jenson and were 0.42 g at the abutment of Los Angeles dam. Newer parts of the plant performed quite well, as did the dam.

Issues: newer compacted fills/designed dams are vast improvements over hydraulic fills; sloshing, etc.



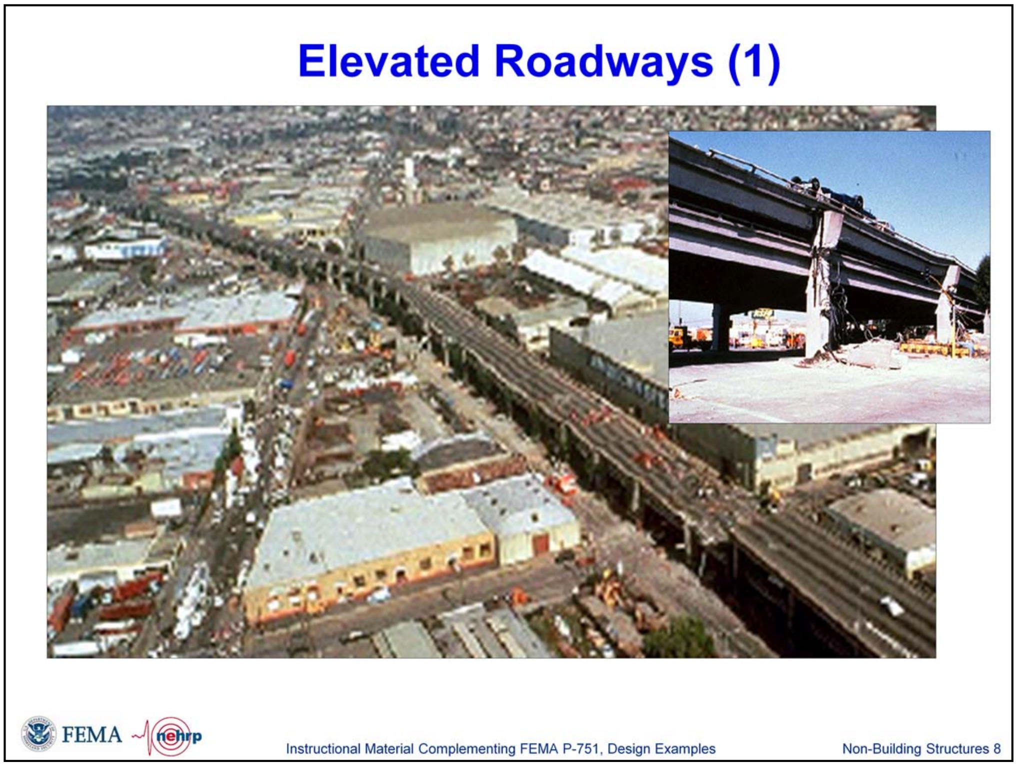
Left (both): Loma Prieta EQ: Struve Slough bridge (1964, concrete T-beam on vertically extended concrete piles, 4 piles per bent)

Right: San Fernando EQ (1971); interchange on San Diego Freeway; failures due to strong ground motions and due to ground failures

Left: Loma Prieta EQ: San Francisco – Oakland Bay bridge, east end of long cantilever truss bridge, small span dropped off seat at expansion joint

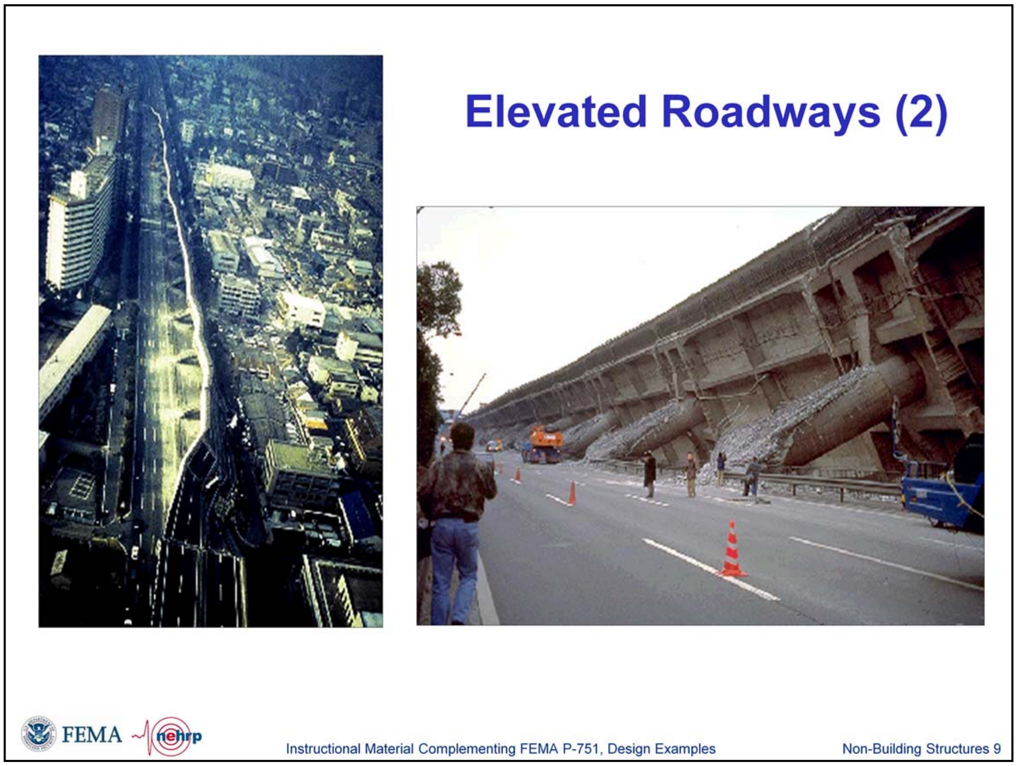
Right: Kobe EQ: Nishinomiya Port arch bridge with similar failure; on Kobe-Osaka freeway; evidence of large soil movement at pier

Issues: large displacements of large structures on soft soils



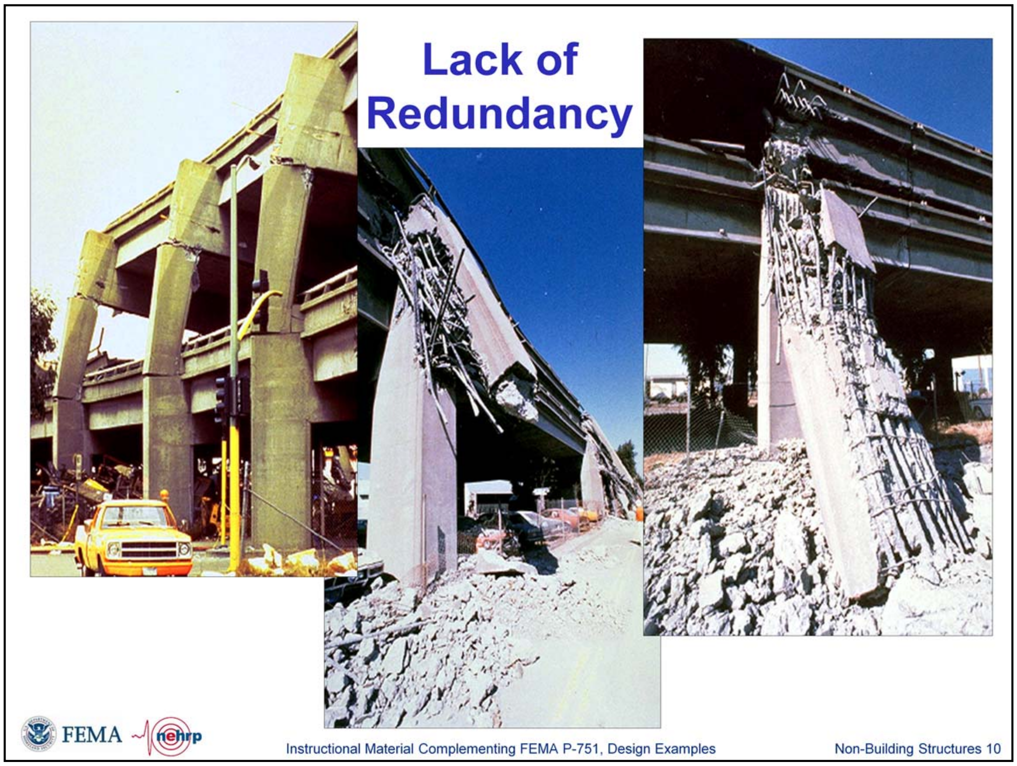
Loma Prieta EQ: Nimitz elevated freeway (I-880, Cyprus viaduct); 50 spans (about 4000 lf) of upper level of two level elevated freeway collapse (out of 124 such spans); 42 fatalities

Issues: very large mass; changes in design considerations over time



Kobe EQ: Hanshin elevated freeway

Issues: massive structures, lack of redundancy

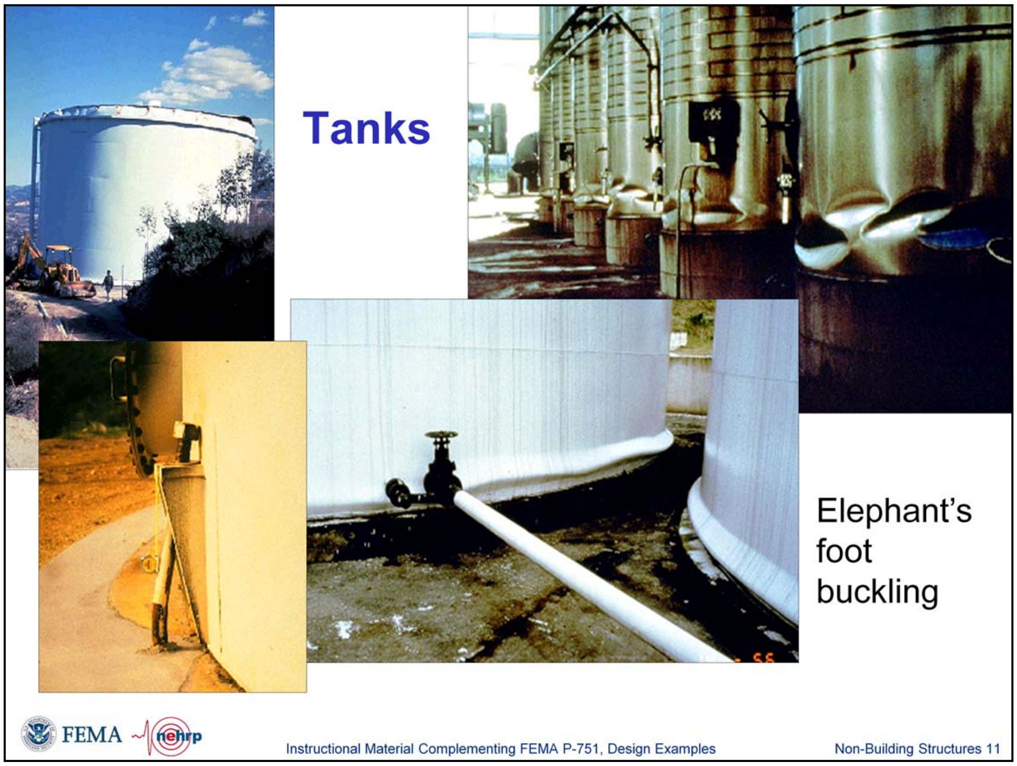


Loma Prieta EQ: Nimitz freeway, Oakland

Left: Upper columns on left side had two hinges; on right side had one hinge, thus upper portal was statically determinate, in order to avoid restraint forces from creep of the post-tensioned girder (1954 design).

Center: Upper column on right side had hinge at its base, thus only moment resisting joint was at the top. Failure here was shear capacity at the lower hinge.

Right: Upper column that completely failed at upper joint



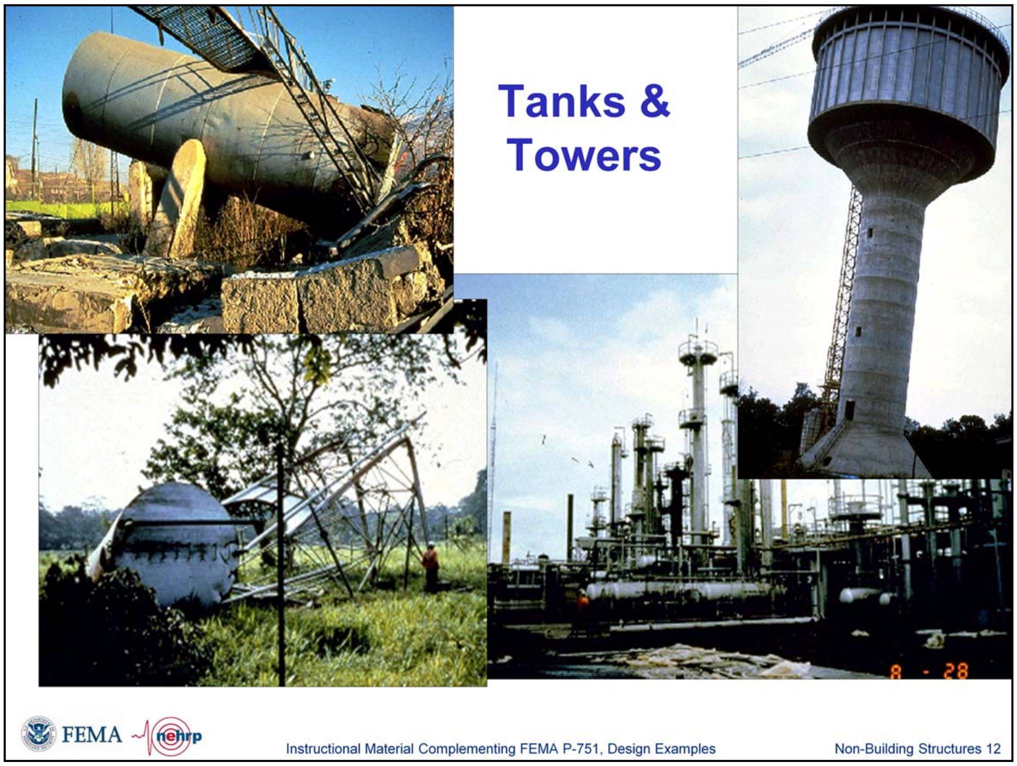
Upper left: Northridge EQ; treated water supply tank. Lost contents due to rupture in piping. Also suffered roof damage and elephant's foot buckling.

Upper right: Coalinga EQ; thin wall stainless steel tanks; elephant's foot buckling at base of tank.

Center: Costa Rica EQ, 1991; benzene storage tanks which buckled but did not fail or lose their contents.

Lower left: Northridge EQ; firewater tank with base anchor bolts.

Issues: fluid-structure interaction; vertical compression in shell due to vertical cantilever action of tank; mass



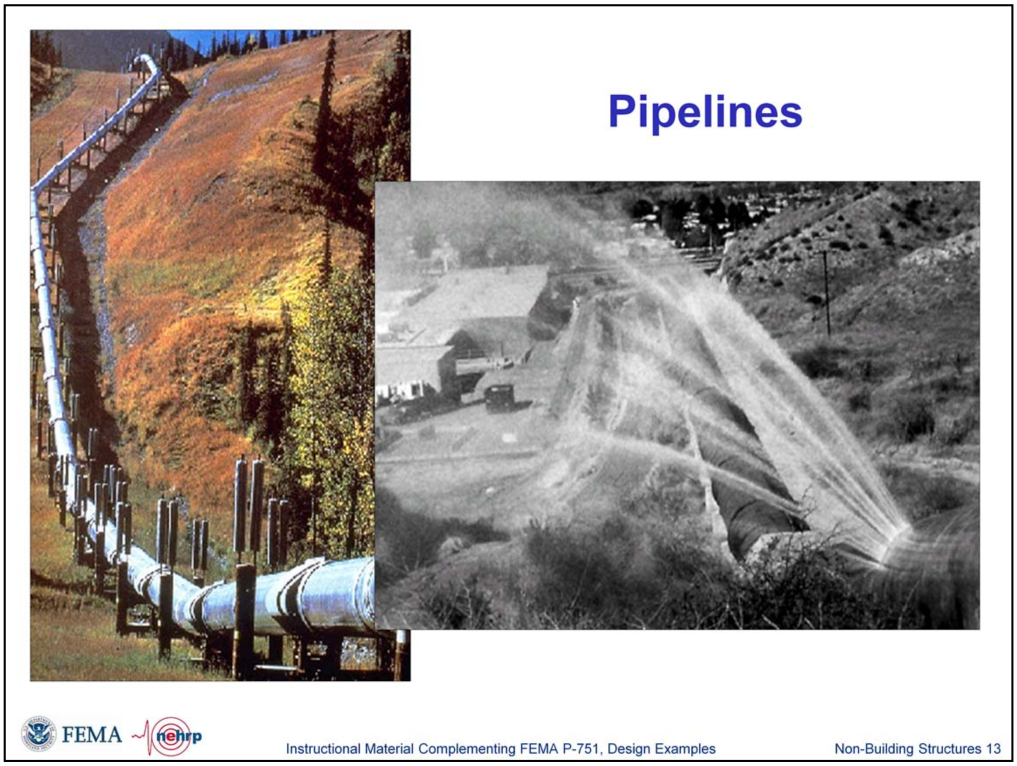
Upper left: Spitak, Armenia EQ; horizontal tank on vertical “saddle” walls; wall at one end overturned, dropping the entire tank and tearing out the piping

Lower left: Costa Rica EQ; elevated tank on trussed tower; apparent buckling of legs

Upper right: Manjil, Iran, 1990; empty water storage tank, just constructed; similar full tank completely destroyed

Lower right: Costa Rica EQ 1991; refinery process columns undamaged; designed for hurricane winds

Issues: large mass, little redundancy



Left: No earthquake damage; Trans-Canada gas transmission pipeline; design must account for potential fault displacement, among many other issues

Right: Northridge EQ; Soledad inverted siphon, 120” diameter, 3/8” wall welded steel water supply system carrying water from the Owens Valley system to Southern California.

Issues: need to resist/accommodate displacements of ground

Right: Kobe EQ: buckling of rails

Center: Northridge EQ; compression failure in 48” water line

Right: Northridge EQ; tension cracks in soil where buried pipe pulled apart; not far from compression photo

Issues: Linear structures must cross zones of likely ground failure; network concepts of system performance are important

Left: Northridge EQ; first observed failure of lattice-type steel transmission line tower; located on a ridge crest and failed due to differential foundation movement; all six conductors snapped, bringing down four adjacent towers

Right: Northridge EQ; Pardee substation; one leg of two legged transmission tower for 220 kV line; 60” square at base, ¾” thick plate, sized for stiffness; weld that did not develop strength of plate. Ten such towers were leaning

Lower: Northridge EQ; Pardee substation; porcelain insulator components damaged at 230 kV live tank circuit breakers

Issues: generally low mass; some components inherently brittle; network concepts

Nonbuilding Structures in NEHRP *Recommended Provisions*

SCOPE of Chapter 15:

- Self supporting structures that carry gravity loads.
- Nonbuilding structures may be supported by earth or by other structures.

EXCLUSIONS:

- Vehicular and railroad bridges
- Nuclear power plants
- Offshore platforms
- Dams

FEMA nehrp Instructional Material Complementing FEMA P-751, Design Examples Non-Building Structures 16

The structural design of the excluded items is covered by other well established standards. For example, structural design of highway bridges is covered by the AASHTO *Bridge Design Specification.* Although it was not at the time the Nimitz elevated freeway was designed.

Nonbuilding Structures

TWO CLASSIFICATIONS included in *Provisions*

1. Nonbuilding structures similar to buildings

- Dynamic response similar to buildings
- Structural systems are designed and constructed similar to buildings
- Use provisions of Chapter 15 and applicable parts of Chapters 11, 12, 14, ...

2. Nonbuilding structures not similar to buildings

- Design and construction results in dynamic response different from buildings
- Use Chapter 15 and “reference documents” for design

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Some nonbuilding structures are quite similar to buildings in their configuration, construction, and dynamic behavior. These structures can be designed using the appropriate sections in the body of the NEHRP *Provisions* with exceptions provided in Chapter 15. Nonbuilding structures not similar to buildings require the use of alternative design provisions which are published in industry standards by such organizations as ASCE, ASME, API (American Petroleum Institute), AWWA (American Water Works Association), and many others. Among the differences between buildings and nonbuilding structures similar to buildings are that partitions and cladding usually add significant damping to buildings. One example of nonbuilding response quite different from buildings is the sloshing of fluids in a tank.

Nonbuilding Structures
defined similar to buildings

Examples:

- Pipe racks
- Steel storage racks
- Electric power generation facilities
- Structural towers for tanks & vessels

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Examples of nonbuilding structures that are considered similar to buildings. The design of steel storage racks should follow the requirements in the RMI design standard, *Specification for the Design, Testing and Utilization of Industrial Steel Storage Racks*. Clearly, damping is not necessarily similar to buildings.

Nonbuilding Structures
not similar to buildings

- Use "reference documents" for design. Loads and load distributions shall not be less than those given by ASCE 7 / NEHRP *Recommended Provisions*.

Examples:

- Earth retaining structures
- Tanks and vessels
- Telecommunication towers
- Stacks and chimneys

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Examples of nonbuilding structures not similar to buildings. Most such structures are designed according to other standards. Chapter 23 lists many such standards. The *Provisions* provide a few additional requirements for the seismic design of these structures–mostly in the Appendix. The primary issue is that the ground motion and design spectrum are based upon the *Provisions.*

Nonbuilding Structures
not similar to buildings

Examples of approved design standards:

- Liquid Storage Tanks:
  - API 620, *Design and Construction of Large, Welded, Low Pressure Storage Tanks*, 11th edition, 2009
  - API 650, *Welded Steel Tanks for Oil Storage*, 11th Edition, Addendum 1, 2008
  - AWWA D100*, Welded Steel Tanks for Water Storage, 2005*
- Pressure Vessels:
  - ASME BPVC-01, *Boiler and Pressure Vessel Code*, 2004 excluding Section III, Nuclear Components, and Section XI, In-Service Inspection of Nuclear Components

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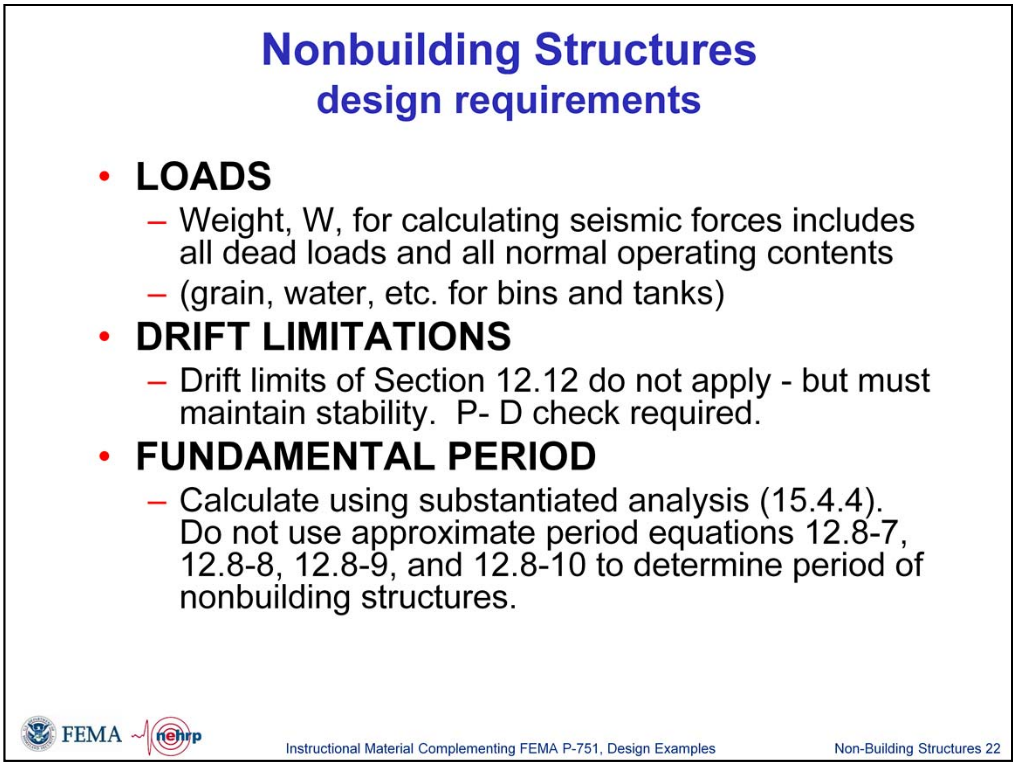
A very brief listing of example design standards. API stands for American Petroleum Institute.

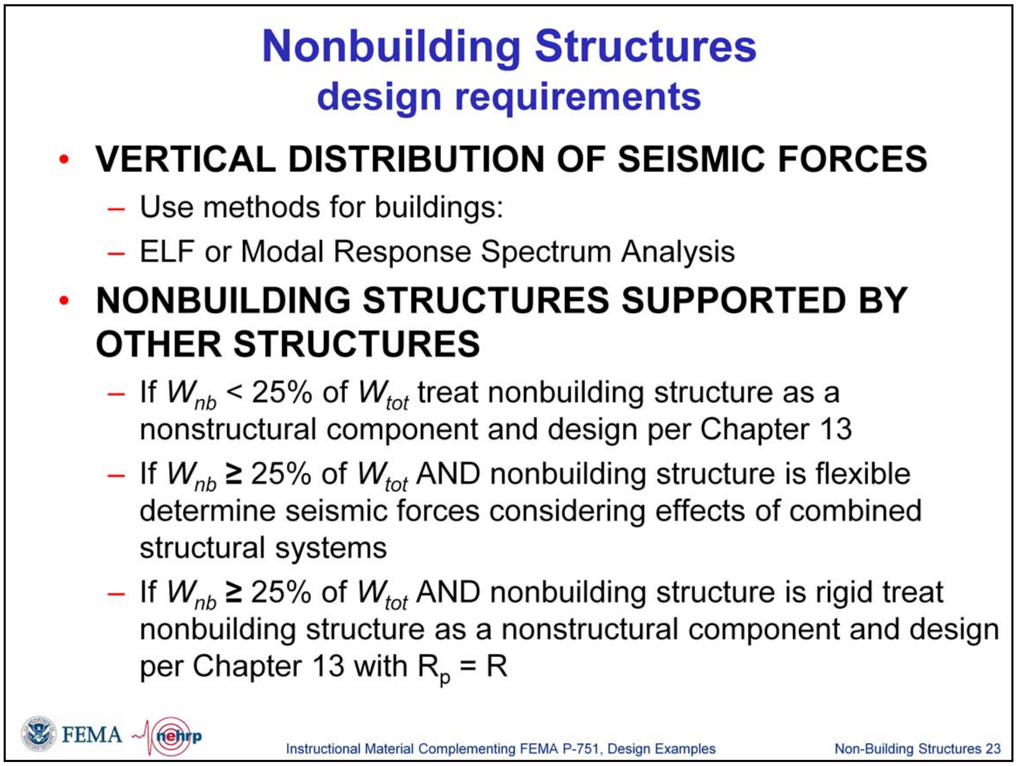


Seismic design requirements and general design rules for nonbuilding structures (Sections 15.4, 15.5, and 15.6).

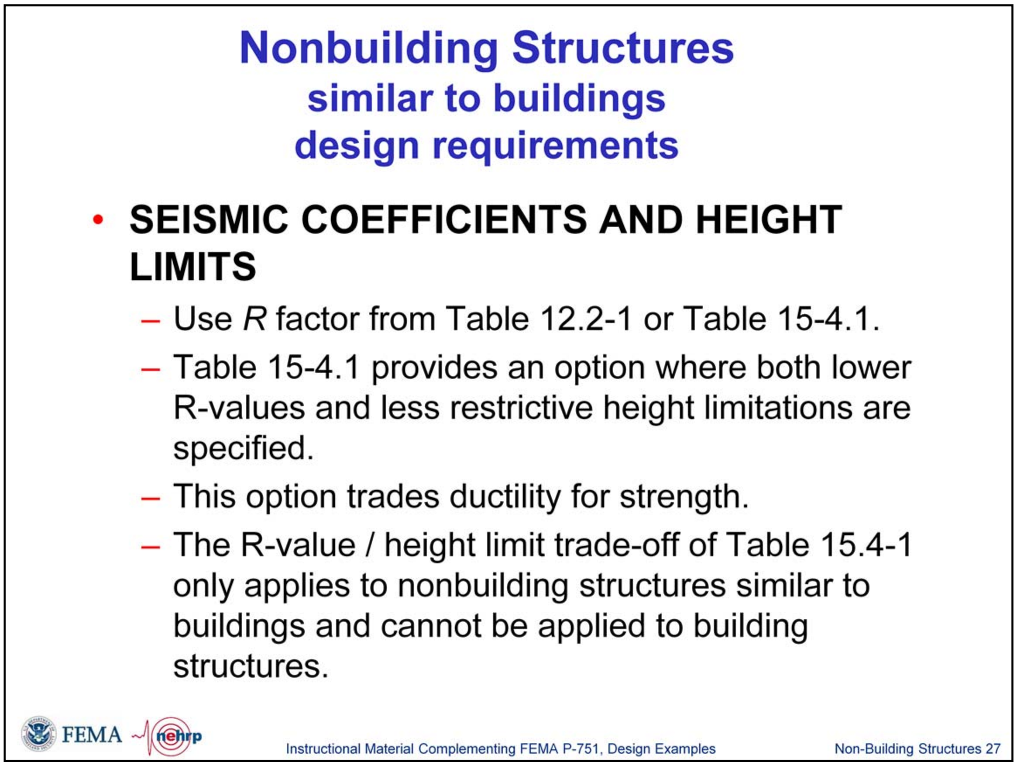
For the design of tanks, bins, vessels, etc., it is necessary to include the total weight of all the operating contents where calculating seismic design forces. This is a slight departure from building structures where only a portion (if any) of the live load is considered in the seismic mass.

Drift limitations for nonbuilding structures are waived because damage control of architectural finishes (cladding, windows) is not an issue.

Special analysis techniques to calculate period are required for nonbuilding structures not similar to buildings.



Nonbuilding structures with irregular distribution of mass are good candidates for modal response spectrum analysis. Where a nonbuilding structure is supported by another structure, the design procedures are dependent on the relative weight of the non-building structure (W_{nb}) and the supporting structure. If the supported nonbuilding structure is relatively light, the design can follow the rules given in Chapter 13 for nonstructural components and attachments. If the supported nonbuilding structure is relatively heavy, the weight and structural system of both structures must be accounted for in the design.



The *Provisions* generally applies the same requirements to nonbuilding structures similar to buildings as it does to buildings. An exception to this is found in Table 15-4.1. R-values, height limits, detailing requirements, and the other related seismic coefficients may be chosen from either Table 12.2-1 or Table 15-4.1 although the mixing and matching of values and requirements from the tables is not allowed. Table 15-4.1 provides significant advantages to selected nonbuilding structures similar to buildings.

Selected nonbuilding structures similar to buildings are provided an option where both lower R-values and less restrictive height limitations are specified. This option permits selected types of nonbuilding structures which have performed well in past earthquakes to be constructed with fewer restrictions in Seismic Design Categories D, E and F provided seismic detailing is used and design force levels are considerably higher. The R-value / height limit trade-off recognizes that the size of some nonbuilding structures is determined by factors other than traditional loadings and result in structures that are much stronger than required for seismic loadings. Therefore, the structure’s ductility demand is generally much lower than a corresponding building. Basically, this option trades ductility for strength. The R-value / height trade-off also attempts to obtain the same structural performance at the increased heights. The user will find that the option of reduced R-value / less restricted height will prove to be the economical choice in most situations due to the relative cost of materials and construction labor. It must be emphasized that the R-value / height limit trade-off of Table 15.4-1 only applies to nonbuilding structures similar to buildings and cannot be applied to building structures.

Nonbuilding Structures
similar to buildings
design requirements

Table 15-4-1—SEISMIC COEFFICIENTS FOR NONBUILDING STRUCTURES SIMILAR TO BUILDINGS

Nonbuilding Structure Type	Detailing Requirements	R	Ω_0	C_d	Structural System and Height Limits (ft.)[a, e]				
					A & B	C	D	E	F
Steel storage racks	15.5.3	4	2	3.5	NL	NL	NL	NL	NL
Building frame systems:									
Special steel concentrically braced frames	AISC 341	6	2	5	NL	NL	160	160	100
Ordinary steel concentrically braced frame	AISC 341	3 ¼	2	3 ¼	NL	NL	35[b]	35[b]	NP[b]
With permitted height increase	AISC 341	2 ½	2	2 ½	NL	NL	160	160	100
With unlimited height	AISC 360	1.5	1	1.5	NL	NL	NL	NL	NL

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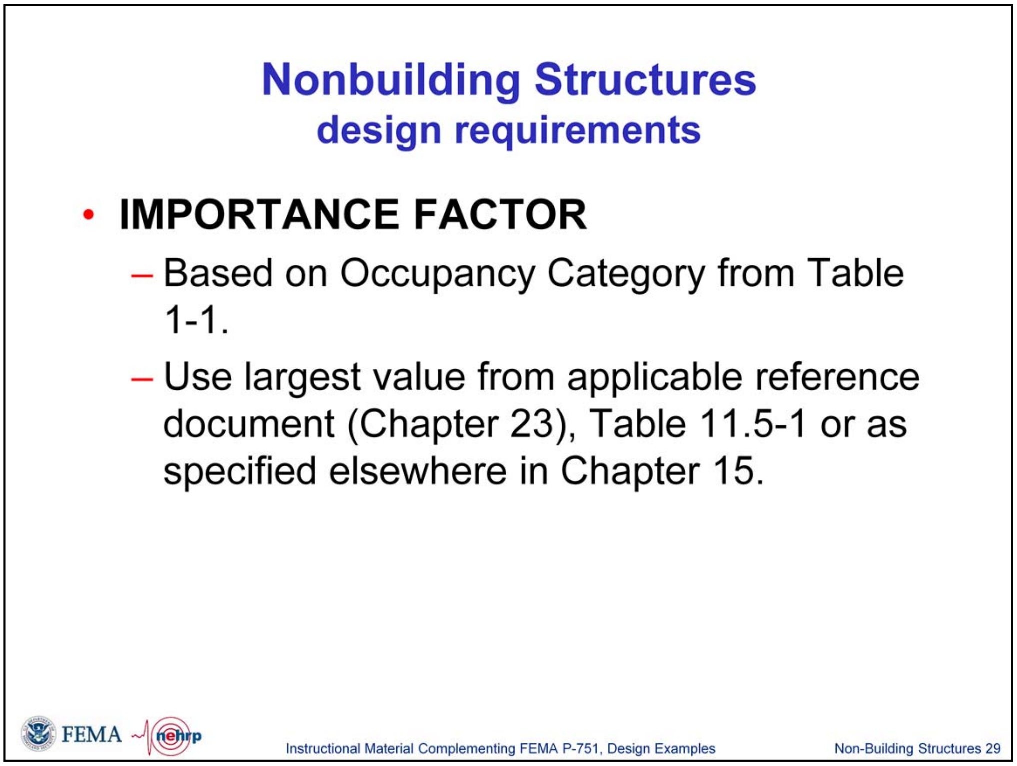
A sample of nonbuilding structural systems similar to buildings. Note that for SDC D, an ordinary steel concentrically braced frame with an *R* value of 3.5 has a 35 ft height limit but has no height limit if an *R* value of 1.5 is used.



The basis for determining importance factors for nonbuilding structures is the same as that for buildings   Structures deemed especially hazardous or critical to post-earthquake recovery are given a larger importance factor.

Nonbuilding Structures
design requirements

- **Table 11.5.1: Importance Factor (I)**

Occupancy Category	I
I or II	1.0
III	1.25
IV	1.5

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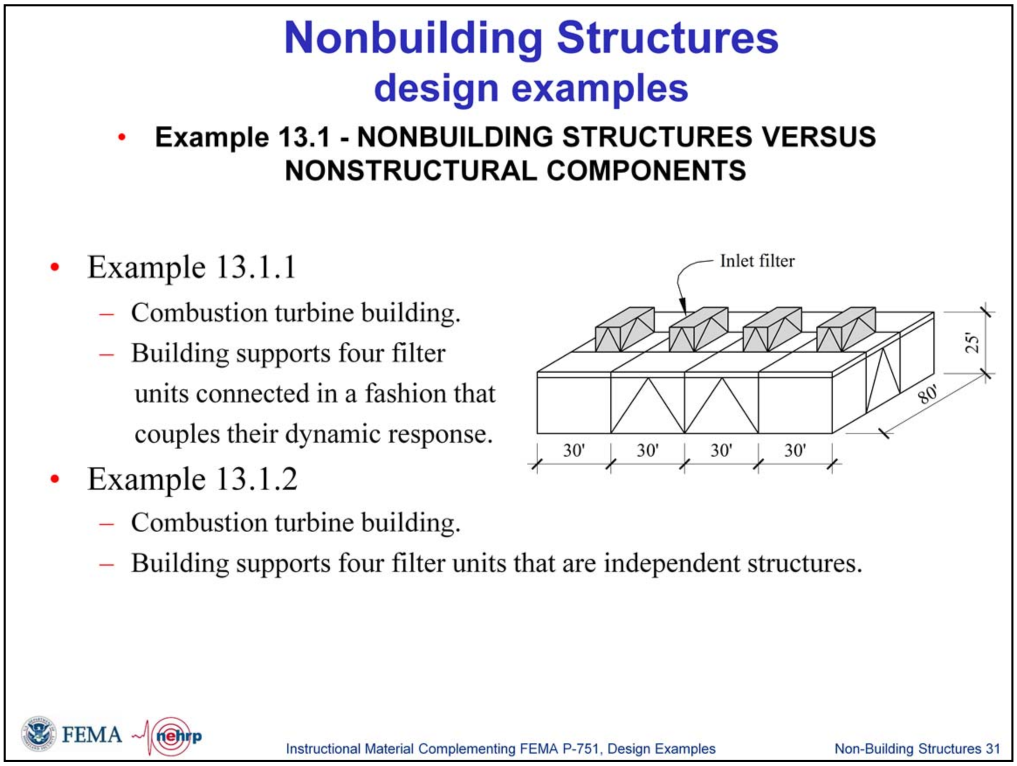
The importance factor is tied to the Occupancy Category specified in Table 1-1. Many nonbuilding structures fall under Occupancy Categories III or IV due the relative hazard presented by toxic or explosive material contained in the structure or due to function performed by the structure such as an essential facility.



The following two examples illustrate the difference between nonbuilding structures that are treated as nonstructural components, using *Standard* Chapter 13, and those which are designed in accordance with *Standard* Chapter 15. In many instances, the weight of the supported nonbuilding structure is relatively small compared to the weight of the supporting structure (less than 25% of the combined weight) such that the supported nonbuilding structure will have a relatively small effect on the overall nonlinear earthquake response of the primary structure during design level ground motions. It is permitted to treat such structures as nonstructural components and use the requirements of *Standard* Chapter 13 for their design. Where the weight of the supported structure is relatively large (greater than or equal to 25% of the combined weight) compared to the weight of the supporting structure, the overall response can be affected significantly. In such cases it is intended that seismic design loads and detailing requirements be determined following the procedures of *Standard* Chapter 15. Where there are multiple large nonbuilding structures, such as vessels supported on a primary nonbuilding structure and the weight of an individual supported nonbuilding structure does not exceed the 25 percent limit but the combined weight of the supported nonbuilding structures does, it is recommended that the combined analysis and design approach of *Standard* Chapter 15 be used.

Nonbuilding Structures
design examples

- Example 13.1.1
  - Four inlet filters = W_{IF} = 4 x 34 kips = 136 kips
  - Support structure = W_{SS} = 288 kips
  - $W_{Combined}$ = 136 kips + 288 kips = 424 kips

$$\frac{W_{IF}}{W_{Combined}} = \frac{136}{424} = 0.321 > 25\%$$

  - Therefore, *Standard* Sec. 15.3.2 is applicable and the requirements of Chapter 15 are to be followed

Because the weight of the inlet filters is 25 percent or more of the combined weight of the nonbuilding structure and the supporting structure (*Standard* Sec. 15.3.2), the inlet filters are classified as “nonbuilding structures” and the seismic design forces must be determined from analysis of the combined seismic-resistant structural systems. This would require modeling the filters, the structural components of the filters, and the structural components of the combustion turbine supporting structure to determine accurately the seismic forces on the structural elements as opposed to modeling the filters as lumped masses.

Nonbuilding Structures
design examples

- Example 13.1.2
  - One (effective) inlet filters = W_{IF} = 34 kips
  - Support structure = W_{SS} = 288 kips
  - $W_{Combined}$ = (4 x 34 kips) + 288 kips = 424 kips

$$\frac{W_{IF}}{W_{Combined}} = \frac{34}{424} = 0.08 < 25\%$$

  - Therefore, *Standard* Sec. 15.3.1 is applicable and the requirements of Chapter 13 are to be followed.

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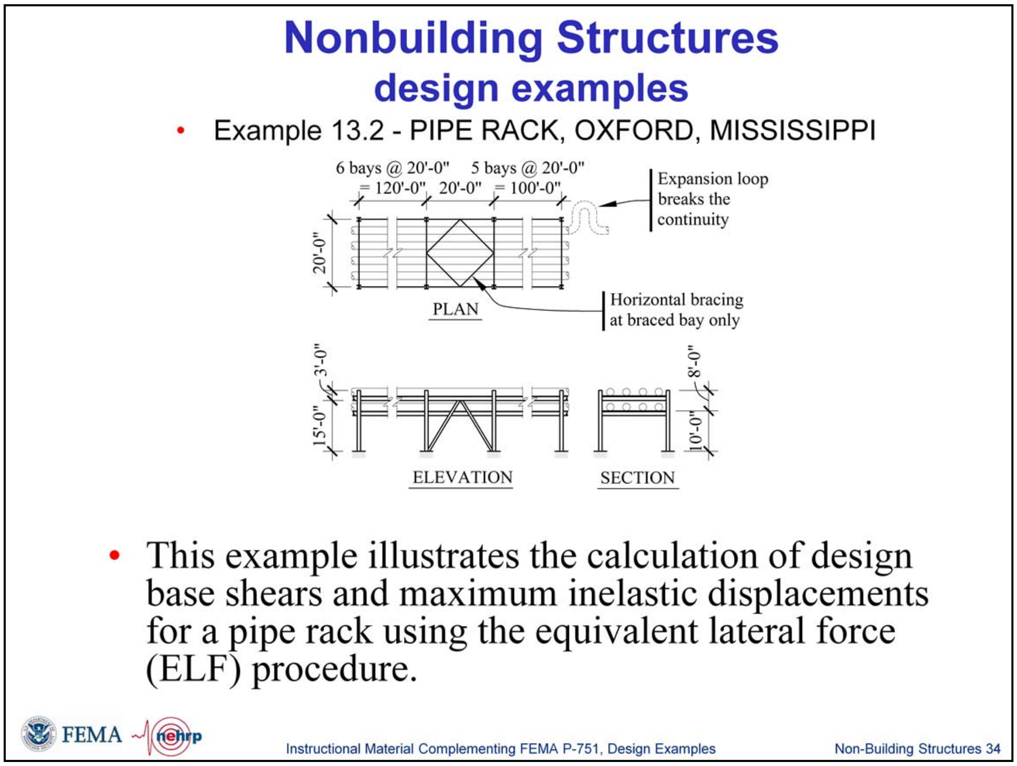
Because the weight of an inlet filter is less than 25 percent of the combined weight of the nonbuilding structures and the supporting structure (*Standard* Sec. 15.3.1), the inlet filters are classified as “nonstructural components” and the seismic design forces must be determined in accordance with *Standard* Chapter 13. In this example, the filters could be modeled as lumped masses. The filters and the filter supports could then be designed as nonstructural components.



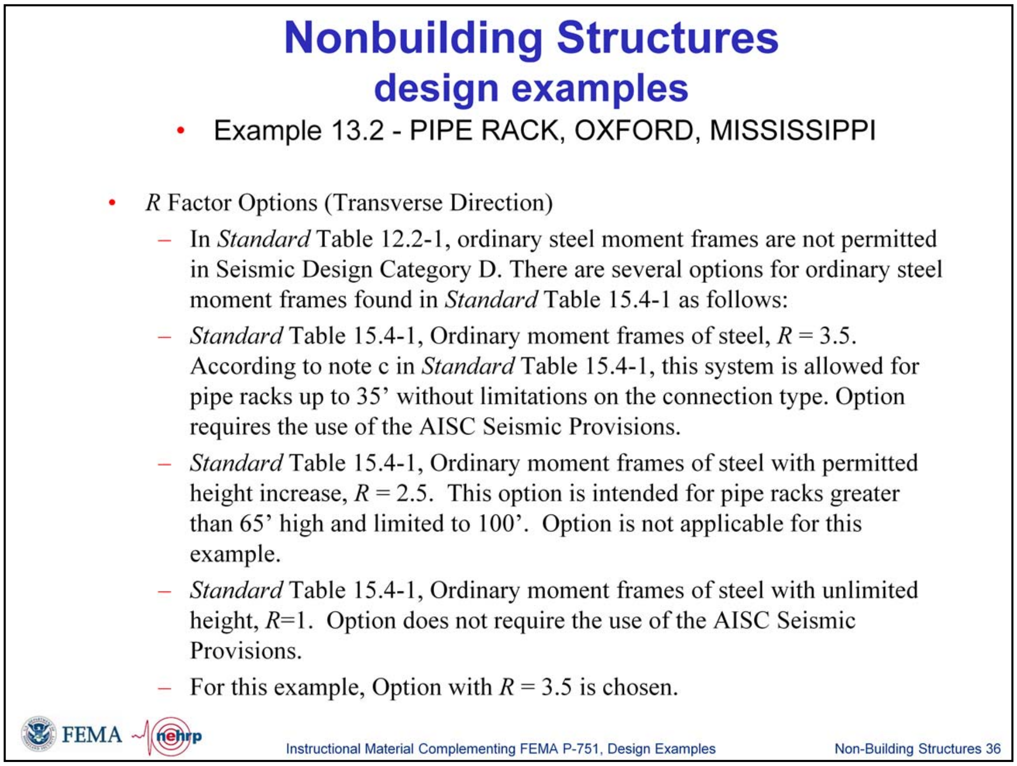
A two-tier, 12-bay pipe rack in a petrochemical facility has concentrically braced frames in the longitudinal direction and ordinary moment frames in the transverse direction. The pipe rack supports four runs of 12-in.-diameter pipe carrying naphtha on the top tier and four runs of 8-in.-diameter pipe carrying water for fire suppression on the bottom tier. The minimum seismic dead load for piping is 35 psf on each tier to allow for future piping loads. The seismic dead load for the steel support structure is 10 psf on each tier.

Nonbuilding Structures
design examples

- Example 13.2 - PIPE RACK, OXFORD, MISSISSIPPI

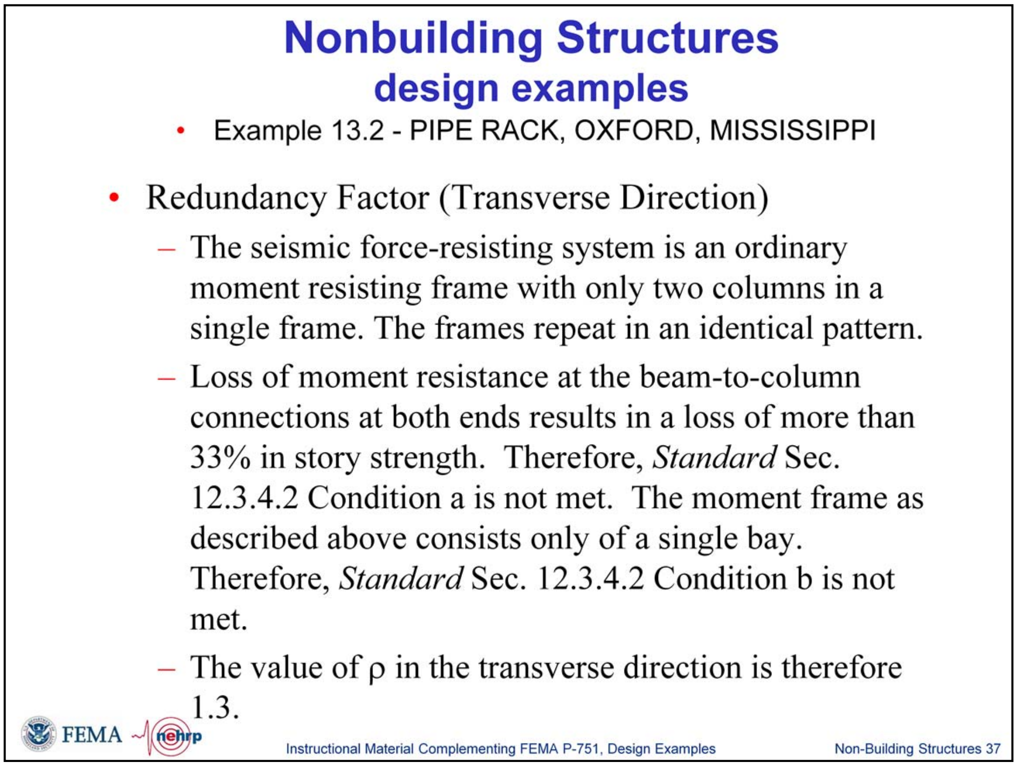
- Importance Factor
  - The upper piping carries a toxic material (naphtha) (Occupancy Category III – *Standard* Table 1-1) and the lower piping is required for fire suppression (Occupancy Category IV – *Standard* Table 1-1). The naphtha piping and the fire water piping are included in *Standard* Sec. 1.5.1; therefore, the pipe rack is assigned to Occupancy Category IV based on the more severe category.
  - From *Standard* Table 11.5-1, I = 1.5

Standard Section 15.4.1.1 directs the user to use the largest value of *I* based on the applicable reference document listed in *Standard* Chapter 23, the largest value selected from *Standard* Table 11.5-1, or as specified elsewhere in *Standard* Chapter 15. It is important to be aware of the requirements of *Standard* Section 15.4.1.1. While the importance factor for most structures will be determined based on *Standard* Table 11.5-1, there are reference documents that define importance factors greater than those found in *Standard* Table 11.5-1. Additionally, *Standard* Sec. 15.5.3 requires that steel storage racks in structures open to the public be assigned an importance factor of 1.5. This additional requirement for steel storage racks addresses a risk to the public that is not addressed by *Standard* Table 11.5-1 and *Standard* Table1-1. For this example, *Standard* Table 11.5-1 governs the choice of importance factor. According to *Standard* Sec. 11.5.1, the importance factor, *I*, is 1.5 based on Occupancy Category IV.

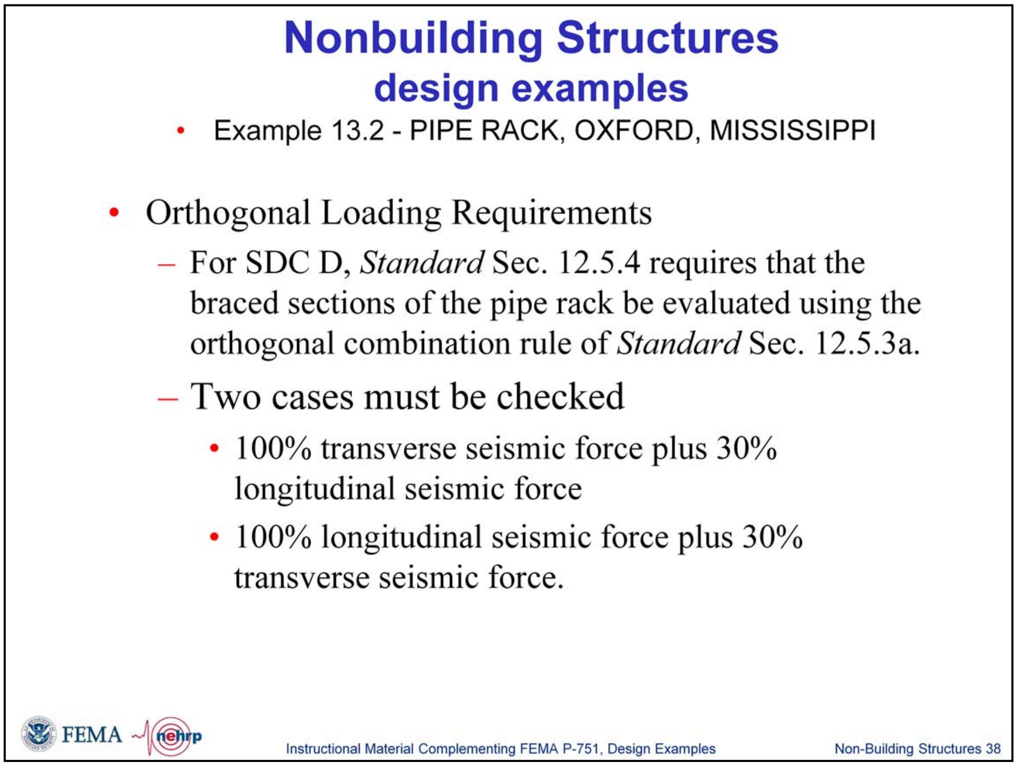


According to *Standard* Section 15.4-1, either *Standard* Table 12.2-1 or *Standard* Table 15.4-1 may be used to determine the seismic parameters although mixing and matching of values and requirements from the tables is not allowed. In *Standard* Chapter 15, selected nonbuilding structures similar to buildings are provided an option where both lower R-values and less restrictive height limitations are specified. This option permits selected types of nonbuilding structures which have performed well in past earthquakes to be constructed with fewer restrictions in Seismic Design Categories D, E and F provided seismic detailing is used and design force levels are considerably higher. The R-value / height limit trade-off recognizes that the size of some nonbuilding structures is determined by factors other than traditional loadings and result in structures that are much stronger than required for seismic loadings. Therefore, the structure’s ductility demand is generally much lower than a corresponding building. The R-value / height trade-off also attempts to obtain the same structural performance at the increased heights. The user will find that the option of reduced R-value / less restricted height will prove to be the economical choice in most situations due to the relative cost of materials and construction labor. It must be emphasized that the R-value / height limit trade-off of *Standard* Table 15.4-1 only applies to nonbuilding structures similar to buildings and cannot be applied to building structures.

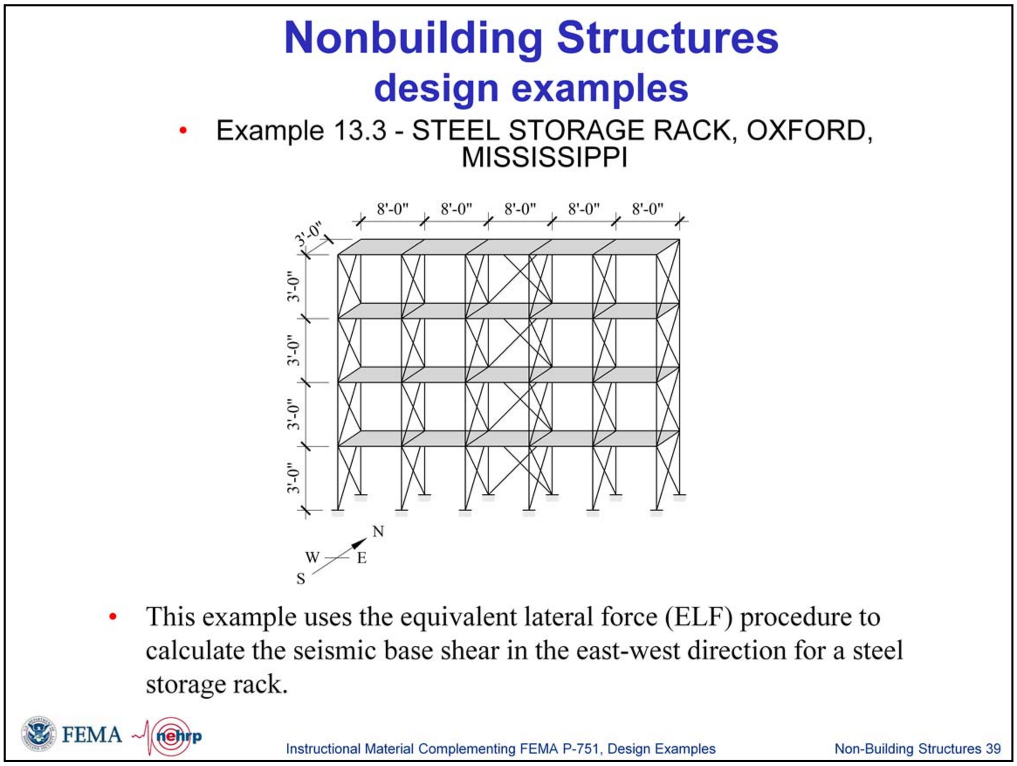
Ordinary steel moment frames are retained for use in nonbuilding structures such as pipe racks because they allow greater flexibility for accommodating process piping and are easier to design and construct than special steel moment frames.



Some nonbuilding structures are designed with parameters from *Standard* Tables 12.2-1 or 15.4-1 if they are termed "nonbuilding structures similar to buildings". For such structures the redundancy factor applies, if the structure is in Seismic Design Category D, E, or F. Pipe racks, being fairly simple moment frames or braced frames, are in the category similar to buildings. Because this structure is assigned to Seismic Design Category D, *Standard* Sec. 12.3.4.2 applies.



Because the pipe rack in this example falls in SDC D, *Standard* Sec. 12.5.4 requires that the braced sections of the pipe rack be evaluated using the orthogonal combination rule of *Standard* Sec. 12.5.3a. Two cases must be checked - 100% transverse seismic force plus 30% longitudinal seismic force and 100% longitudinal seismic force plus 30% transverse seismic force. The vertical seismic force represented by $0.2S_{DS}D$ is only applied once in each load case. Do not include the vertical seismic force in with both horizontal seismic load combinations. In this pipe rack example, due to the bracing configuration, the foundation and column anchorage would be the only components impacted by the orthogonal load combinations.



A four-tier, five-bay steel storage rack is located in a retail discount warehouse. There are concentrically braced frames in the north-south and east-west directions. The general public has direct access to the aisles and merchandise is stored on the upper racks. The rack is supported on a slab on grade. The design operating load for the rack contents is 125 psf on each tier. The weight of the steel support structure is assumed to be 5 psf on each tier.

Nonbuilding Structures
design examples

- Example 13.3 - STEEL STORAGE RACK, OXFORD, MISSISSIPPI

- Importance Factor
  - Use *Standard* Sec. 1.5.1. The storage rack is in a retail facility. Therefore the storage rack is assigned to Occupancy Category II. According to *Standard* Sec. 15.5.3(2) , $I = I_p = 1.5$ because the rack is in an area open to the general public.
- RMI Section 2.6.2 Loading Conditions
  - Load Case 1 – Each rack loaded.
  - Load Case 2 – Only top rack loaded.

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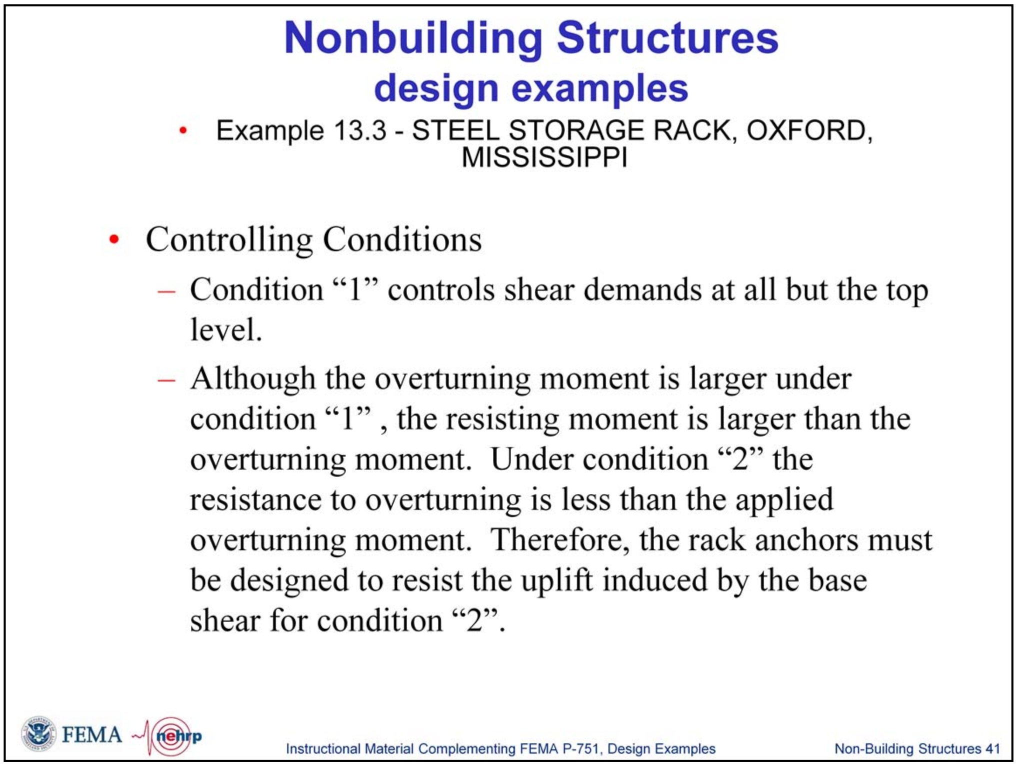
Standard Sec. 15.5.3 allows designers some latitude in selecting the seismic design methodology. Designers may use the Rack Manufacturer's Institute specification (MH 16.1-2008) to design steel storage racks. In other words, racks designed using the RMI method of Sec. 15.5.3 are deemed to comply. As an alternate, designers may use the requirements of *Standard* Sec. 15.5.3.1 through 15.5.3.4.

In this example, the requirements of the Rack Manufacturer's Institute specification (MH 16.1-2008) are used.



In order to calculate the design forces, shears, and overturning moments at each level, seismic forces must be distributed vertically in accordance with *RMI* Sec. 2.6.6 for Load Condition “1”.

It should be noted that the distribution of east-west seismic shear will induce torsion in the rack system because the east-west brace is only on the back of the storage rack. The torsion should be resisted by the north-south braces at each end of the bay where the east-west braces are placed. If the torsion were to be distributed to each end of the storage rack, the engineer would be required to calculate the transfer of torsional forces in diaphragm action in the shelving, which may be impractical.

13

Nonbuilding Structure Design

By J. G. (Greg) Soules, P.E., S.E.
Originally developed by Harold O. Sprague, Jr., P.E.

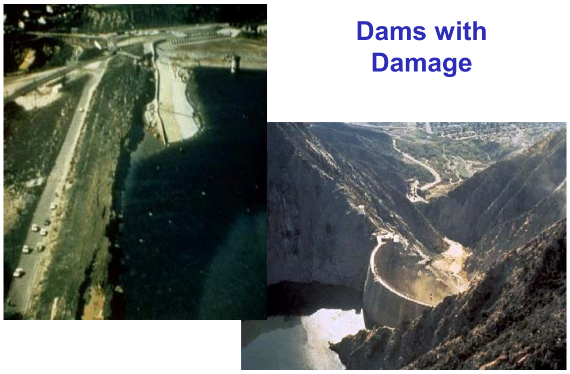
Nonbuilding Structures

Nonbuilding Structures

Same:
- Basic ground motion hazards
- Basic structural dynamics

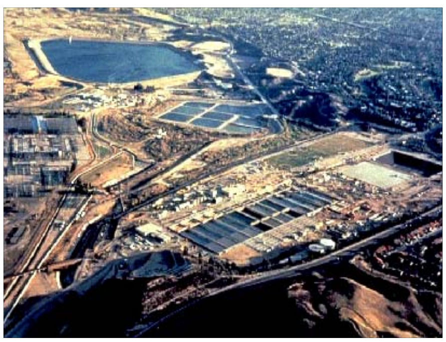
Different:
- Structural characteristics
- Fault rupture
- Fluid dynamics
- Performance objectives
- Networked systems

Dams with Damage



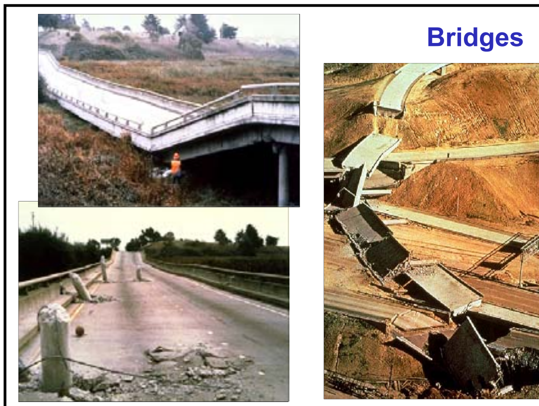
FEMA nehrp

Dam and Water Treatment Plant



FEMA nehrp

Bridges



FEMA nehrp

Joints at Long Spans

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Elevated Roadways (1)

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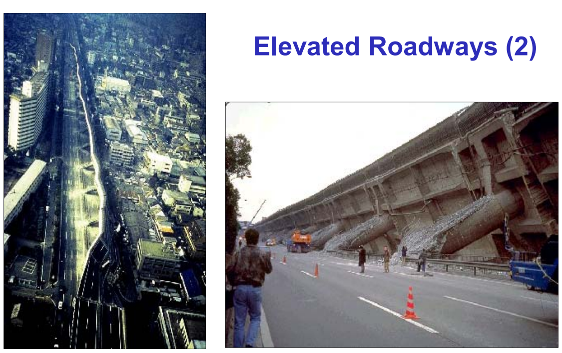
Elevated Roadways (2)



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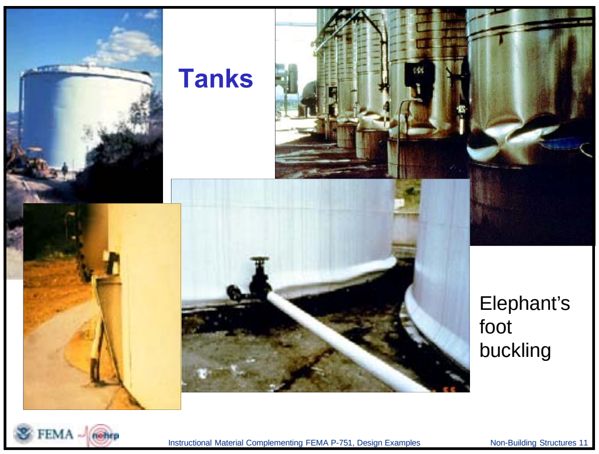
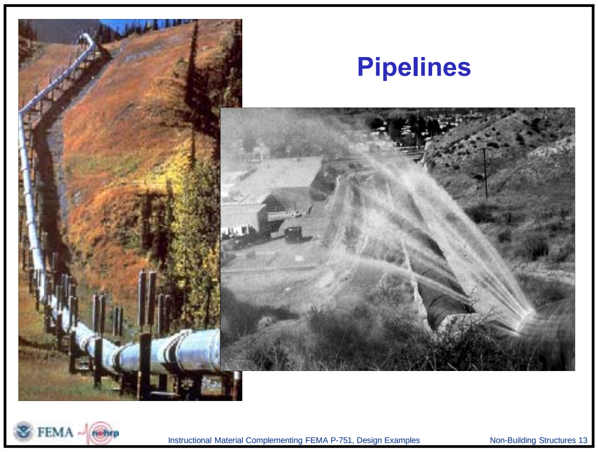
Lack of
Redundancy
FEMA
Instructional Material Complementing FEMA P-751, Design Examples
Non-Building Structures 10


Tanks
Elephant's
foot
buckling
FEMA
Instructional Material Complementing FEMA P-751, Design Examples
Non-Building Structures 11


Tanks &
Towers
FEMA
Instructional Material Complementing FEMA P-751, Design Examples
Non-Building Structures 12


Pipelines
FEMA
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Instructional Material Complementing FEMA P-751, Design Examples
Non-Building Structures 13


On-Grade and Buried
FEMA
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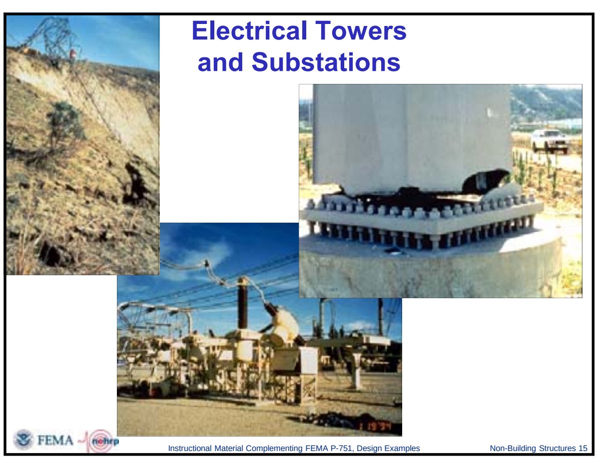
Instructional Material Complementing FEMA P-751, Design Examples
Non-Building Structures 14


Electrical Towers
and Substations
FEMA
nehrp
Instructional Material Complementing FEMA P-751, Design Examples
Non-Building Structures 15

Nonbuilding Structures in NEHRP *Recommended Provisions*

SCOPE of Chapter 15:

- Self supporting structures that carry gravity loads.
- Nonbuilding structures may be supported by earth or by other structures.

EXCLUSIONS:

- Vehicular and railroad bridges
- Nuclear power plants
- Offshore platforms
- Dams

Nonbuilding Structures

TWO CLASSIFICATIONS included in *Provisions*

1. Nonbuilding structures similar to buildings

- Dynamic response similar to buildings
- Structural systems are designed and constructed similar to buildings
- Use provisions of Chapter 15 and applicable parts of Chapters 11, 12, 14, ...

2. Nonbuilding structures not similar to buildings

- Design and construction results in dynamic response different from buildings
- Use Chapter 15 and "reference documents" for design

Nonbuilding Structures
defined similar to buildings

Examples:

- Pipe racks
- Steel storage racks
- Electric power generation facilities
- Structural towers for tanks & vessels

Nonbuilding Structures
design requirements

Example of Structural Tower that is not Integral with the Supported Tank

Example of Structural Tower that is Integral with the Supported Tank

Nonbuilding Structures
not similar to buildings

- Use “reference documents” for design. Loads and load distributions shall not be less than those given by ASCE 7 / NEHRP *Recommended Provisions*.

Examples:

- Earth retaining structures
- Tanks and vessels
- Telecommunication towers
- Stacks and chimneys

Nonbuilding Structures
not similar to buildings

Examples of approved design standards:

- Liquid Storage Tanks:
  - API 620, *Design and Construction of Large, Welded, Low Pressure Storage Tanks*, 11th edition, 2009
  - API 650, *Welded Steel Tanks for Oil Storage*, 11th Edition, Addendum 1, 2008
  - AWWA D100*, Welded Steel Tanks for Water Storage, 2005*
- Pressure Vessels:
  - ASME BPVC-01, *Boiler and Pressure Vessel Code*, 2004 excluding Section III, Nuclear Components, and Section XI, In-Service Inspection of Nuclear Components

Nonbuilding Structures
design requirements

- **LOADS**
  - Weight, W, for calculating seismic forces includes all dead loads and all normal operating contents
  - (grain, water, etc. for bins and tanks)
- **DRIFT LIMITATIONS**
  - Drift limits of Section 12.12 do not apply - but must maintain stability. P- D check required.
- **FUNDAMENTAL PERIOD**
  - Calculate using substantiated analysis (15.4.4). Do not use approximate period equations 12.8-7, 12.8-8, 12.8-9, and 12.8-10 to determine period of nonbuilding structures.

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Nonbuilding Structures
design requirements

- **VERTICAL DISTRIBUTION OF SEISMIC FORCES**
  - Use methods for buildings:
  - ELF or Modal Response Spectrum Analysis
- **NONBUILDING STRUCTURES SUPPORTED BY OTHER STRUCTURES**
  - If W_{nb} < 25% of W_{tot} treat nonbuilding structure as a nonstructural component and design per Chapter 13
  - If W_{nb} ≥ 25% of W_{tot} AND nonbuilding structure is flexible determine seismic forces considering effects of combined structural systems
  - If W_{nb} ≥ 25% of W_{tot} AND nonbuilding structure is rigid treat nonbuilding structure as a nonstructural component and design per Chapter 13 with $R_p = R$

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Nonbuilding Structures
design requirements

- Nonbuilding structures supported by other structures see amplified seismic forces in a similar manner as nonstructural components.
- Section 15.3 of ASCE 7 / NEHRP *Recommended Provisions* provides extensive guidance on the design of nonbuilding structures supported by other structures.
- There are 3 possible outcomes when the provisions of Section 15.3 are used as mentioned in the previous slide.

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Nonbuilding Structures
design requirements

- Unfortunately, Table 15.4-2 (nonbuilding structures not similar to buildings) contains an error, which conflicts with the provisions of Section 15.3.
- The 3rd entry in Table 15.4-2 is: "Tanks or vessels supported on structural towers similar to buildings".
- The entry goes on to say: "Use values for the appropriate structure type in the categories for building frame systems and moment resisting frame systems listed in Table 12.2-1 or Table 15.4-1."
- This entry was not coordinated with Section 15.3 and assumes that the supported tank or vessel is rigid.

Nonbuilding Structures
design requirements

- Most tanks and vessels supported on structural towers will be flexible, especially if fluid-structure interaction is accounted for and/or the flexibility of the support beams is taken into account.
- This entry in Table 15.4-2 has been proposed to be deleted in ASCE 7-10 Supplement 2 and in the 2014 NEHRP *Recommended Provisions*.
- I recommend that you mark through this table entry now!

Nonbuilding Structures
similar to buildings
design requirements

- **SEISMIC COEFFICIENTS AND HEIGHT LIMITS**
  - Use *R* factor from Table 12.2-1 or Table 15-4.1.
  - Table 15-4.1 provides an option where both lower R-values and less restrictive height limitations are specified.
  - This option trades ductility for strength.
  - The R-value / height limit trade-off of Table 15.4-1 only applies to nonbuilding structures similar to buildings and cannot be applied to building structures.

Nonbuilding Structures
similar to buildings
design requirements

Table 15-4-1—SEISMIC COEFFICIENTS FOR NONBUILDING STRUCTURES SIMILAR TO BUILDINGS

Nonbuilding Structure Type	Detailing Requirements	R	Ω_0	C_d	Structural System and Height Limits (ft.)[a, c]				
					A & B	C	D	E	F
Steel storage racks	15.5.3	4	2	3.5	NL	NL	NL	NL	NL
Building frame systems:									
Special steel concentrically braced frames	AISC 341	6	2	5	NL	NL	160	160	100
Ordinary steel concentrically braced frame	AISC 341	3 ¼	2	3 ¼	NL	NL	35[b]	35[b]	NP[b]
With permitted height increase	AISC 341	2 ½	2	2 ½	NL	NL	160	160	100
With unlimited height	AISC 360	1.5	1	1.5	NL	NL	NL	NL	NL

Nonbuilding Structures
design requirements

- **IMPORTANCE FACTOR**
  – Based on Occupancy Category from Table 1-1.
  – Use largest value from applicable reference document (Chapter 23), Table 11.5-1 or as specified elsewhere in Chapter 15.

Nonbuilding Structures
design requirements

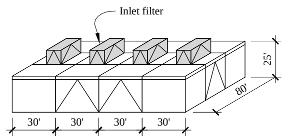
- **Table 11.5.1: Importance Factor (I)**

Occupancy Category	I
I or II	1.0
III	1.25
IV	1.5

Nonbuilding Structures
design examples

- **Example 13.1 - NONBUILDING STRUCTURES VERSUS NONSTRUCTURAL COMPONENTS**

- Example 13.1.1
  - Combustion turbine building.
  - Building supports four filter units connected in a fashion that couples their dynamic response.
- Example 13.1.2
  - Combustion turbine building.
  - Building supports four filter units that are independent structures.



Nonbuilding Structures
design examples

- Example 13.1.1
  - Four inlet filters = W_{IF} = 4 x 34 kips = 136 kips
  - Support structure = W_{SS} = 288 kips
  - $W_{Combined}$ = 136 kips + 288 kips = 424 kips

$$\frac{W_{IF}}{W_{Combined}} = \frac{136}{424} = 0.321 > 25\%$$

  - Therefore, *Standard* Sec. 15.3.2 is applicable and the requirements of Chapter 15 are to be followed

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- Example 13.1.2
  - One (effective) inlet filters = W_{IF} = 34 kips
  - Support structure = W_{SS} = 288 kips
  - $W_{Combined}$ = (4 x 34 kips) + 288 kips = 424 kips

$$\frac{W_{IF}}{W_{Combined}} = \frac{34}{424} = 0.08 < 25\%$$

  - Therefore, *Standard* Sec. 15.3.1 is applicable and the requirements of Chapter 13 are to be followed.

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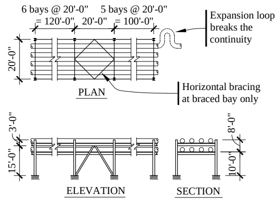
- Example 13.2 - PIPE RACK, OXFORD, MISSISSIPPI



- This example illustrates the calculation of design base shears and maximum inelastic displacements for a pipe rack using the equivalent lateral force (ELF) procedure.

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- Example 13.2 - PIPE RACK, OXFORD, MISSISSIPPI

- Importance Factor
  - The upper piping carries a toxic material (naphtha) (Occupancy Category III – *Standard* Table 1-1) and the lower piping is required for fire suppression (Occupancy Category IV – *Standard* Table 1-1). The naphtha piping and the fire water piping are included in *Standard* Sec. 1.5.1; therefore, the pipe rack is assigned to Occupancy Category IV based on the more severe category.
  - From *Standard* Table 11.5-1, $I = 1.5$

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- Example 13.2 - PIPE RACK, OXFORD, MISSISSIPPI

- R Factor Options (Transverse Direction)
  - In *Standard* Table 12.2-1, ordinary steel moment frames are not permitted in Seismic Design Category D. There are several options for ordinary steel moment frames found in *Standard* Table 15.4-1 as follows:
  - *Standard* Table 15.4-1, Ordinary moment frames of steel, $R = 3.5$. According to note c in *Standard* Table 15.4-1, this system is allowed for pipe racks up to 35' without limitations on the connection type. Option requires the use of the AISC Seismic Provisions.
  - *Standard* Table 15.4-1, Ordinary moment frames of steel with permitted height increase, $R = 2.5$. This option is intended for pipe racks greater than 65' high and limited to 100'. Option is not applicable for this example.
  - *Standard* Table 15.4-1, Ordinary moment frames of steel with unlimited height, R=1. Option does not require the use of the AISC Seismic Provisions.
  - For this example, Option with $R = 3.5$ is chosen.

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- Example 13.2 - PIPE RACK, OXFORD, MISSISSIPPI

- Redundancy Factor (Transverse Direction)
  - The seismic force-resisting system is an ordinary moment resisting frame with only two columns in a single frame. The frames repeat in an identical pattern.
  - Loss of moment resistance at the beam-to-column connections at both ends results in a loss of more than 33% in story strength. Therefore, *Standard* Sec. 12.3.4.2 Condition a is not met. The moment frame as described above consists only of a single bay. Therefore, *Standard* Sec. 12.3.4.2 Condition b is not met.
  - The value of ρ in the transverse direction is therefore 1.3.

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- Example 13.2 - PIPE RACK, OXFORD, MISSISSIPPI

- Orthogonal Loading Requirements
  - For SDC D, *Standard* Sec. 12.5.4 requires that the braced sections of the pipe rack be evaluated using the orthogonal combination rule of *Standard* Sec. 12.5.3a.
  - Two cases must be checked
    - 100% transverse seismic force plus 30% longitudinal seismic force
    - 100% longitudinal seismic force plus 30% transverse seismic force.

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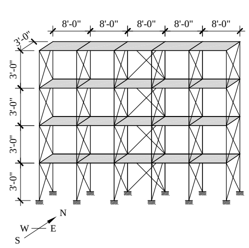
- Example 13.3 - STEEL STORAGE RACK, OXFORD, MISSISSIPPI



- This example uses the equivalent lateral force (ELF) procedure to calculate the seismic base shear in the east-west direction for a steel storage rack.

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- Example 13.3 - STEEL STORAGE RACK, OXFORD, MISSISSIPPI

- Importance Factor
  - Use *Standard* Sec. 1.5.1. The storage rack is in a retail facility. Therefore the storage rack is assigned to Occupancy Category II. According to *Standard* Sec. 15.5.3(2) , $I = I_p = 1.5$ because the rack is in an area open to the general public.
- RMI Section 2.6.2 Loading Conditions
  - Load Case 1 – Each rack loaded.
  - Load Case 2 – Only top rack loaded.

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- Example 13.3 - STEEL STORAGE RACK, OXFORD, MISSISSIPPI

- Controlling Conditions
  - Condition "1" controls shear demands at all but the top level.
  - Although the overturning moment is larger under condition "1" , the resisting moment is larger than the overturning moment. Under condition "2" the resistance to overturning is less than the applied overturning moment. Therefore, the rack anchors must be designed to resist the uplift induced by the base shear for condition "2".

Questions?